Thesis / Reports O'Hara, K.L.

DESIGN A DECISION SUPPORT SYSTEM LINKING SILVICULTURAL TREATMENTS AND FOREST HEALTH IN A LANDSCAPE MANAGEMENT CONTEXT

FINAL REPORT

RJVA No. INT-94927-RJVA
between
U.S. Department of Agriculture, Forest Service, Intermountain Research Station
and
University of Montana

"Construction and Validation of an Ecosystem-Level Decision Support System Integrating Silvicultural Treatments, Forest Health, and Stand Structure on the Bitterroot National Forest"

Prepared by:
Kevin L. O'Hara, Elizabeth Brantley, and Anne Karsian
School of Forestry
University of Montana
Missoula, MT 59812

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FINAL REPORT FOR RESEARCH AGREEMENT
#INT-94927-RJVA
"Design a Decision Support System linking Silvicultural Treatments and Forest Health in a Landscape Management Context"
UNIVERSITY OF MONTANA
FS Contact: Dr. Elizabeth Reinhardt
CoOp Contact: Dr. Kevin O'Hara

The University of
Montana

School of Forestry
The University of Montana
Missoula, Montana 59812
(406) 243-5521
(406) 243-4845 FAX

June 19, 1995

Elizabeth Reinhardt
Intermountain Fire Sciences Laboratory
USDA Forest Service
P.O. Box 8089
Missoula, MT 59807

Dear Liz:

Enclosed are two copies of the final report for the Research Joint Venture Agreement No. INT-94927-RJVA entitled: "Construction and validation of an ecosystem-level decision support system integrating silvicultural treatments, forest health, and stand structure on the Bitterroot National Forest." The final report consists of the revised, final study plan and a master's thesis that was partially funded on the RJVA. This study plan describes the three-year plan to measure ecological parameters and develop the decision support system.

The project will not proceed beyond Phase 1 since the graduate student, Elizabeth Brantley, has left the University of Montana. Existing personnel at the University of Montana are not sufficient to continue this project. This is unfortunate because the project objectives are worthy of additional study and would provide a valuable tool for forest land managers.

Please also note that the RJVA also provided support for completion of Anne Karsian's thesis study of the pollen record of Mary's Frog Pond, Montana. This project was completed on schedule and the final thesis is also included in the final report.

I regret we are not able to complete phases 2 and 3 of the decision support system. Please contact me if you have questions.

Sincerely,

Kevin L. O'Hara
Associate Professor of Silviculture
(406) 243-5675

The University of
Montana

School of Forestry
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Available Data Sources

Three potential data sources are described in the attached study plan: 1) Existing published studies and scientific opinion; 2) Broad-scale sampling data; and 3) growth and yield model projections. All three appear to be suitable sources of data. The broad-scale sampling data are the primary data source since previous studies have not been directly linked to biophysical environments or stand structural classifications. Through integration of vegetation measurements with structural classifications and biophysical environments, the broad-scale sampling data will provide the necessary linkage between these variables.

Existing published studies will provide important data, however. Both published and unpublished (expert opinion) studies will provide valuable linkages between broad-scale sampling data and insect and pathogen incidence that may not be observed in years sampled in this study. For example, low spruce budworm activity in 1995 and 1996 will require integration of observed spruce budworm activity in previous outbreak years with vegetation characteristics observed in broad-scale sampling. Both published studies and scientific opinion will be useful for this purpose. The Columbia River Basin assessment has been successfully using expert opinion on insect and pathogen incidence in relation to structural stage development to develop parameters for the CRB-SUM model.

Stand projection systems will provide the estimates of change in vegetation structure over time. Existing growth and yield models like Prognosis or the stand structural stage models being developed at the University of Montana will be used for these projections. The decision support system must not only estimate potential insect and pathogen incidence in current structures but also anticipate future structural changes. From these projected stand structural changes, estimates of future insect and pathogen incidence can be estimated providing the basis for recommendations for land management strategies.

Conclusions

Development of a decision support system to assist land managers with decisions related to vegetation change and forest health appears to be an essential tool in an ecosystem management framework. Integration of biophysical elements and stand structures appears to be a logical basis for anticipating forest health effects and prescribing silvicultural activities to ameliorate undesirable forest health conditions. The key to avoiding many forest health problems is a proactive management approach that antipates future vegetation change and potential incidence of insect and pathogens. This study can provide a tool for anticipating insect and pathogen activity.

Proposed data sources and methodology appear to be a reasonable approach to development of this decision support system. The broad-scale sampling data for identifying vegetative

structure over large scales and relative insect and pathogen activity is the cornerstone of this project. Previous research will provide valuable linkages to more detailed observations of insect and pathogen problems, and stand growth projection systems will estimate future vegetation change.

Construction and Validation of an Ecosystem-Level Decision Support System Integrating Silvicultural Treatments, Forest Health, and Stand Structure on the Bitterroot National Forest

A study plan for the Bitterroot Ecosystem Management Project

Principle Investigators:
Kevin O'Hara, Associate Professor
Elizabeth Brantley, Graduate Student
School of Forestry
University of Montana
Missoula, MT 59812

September 30, 1994

INTRODUCTION

Changes in management objectives and focus on ecosystem-level processes are leading to the development and use of alternative silvicultural systems in the inland Pacific Northwest. These systems produce structures that may be more susceptible to a variety of forest health problems (insects and pathogens) than traditional structures. For example, greater use of uneven-aged systems in some forest types will create multi-story stands of tolerant species that are subject to western spruce budworm and a variety of root pathogens (Haack and Byler, 1993). As we begin to implement ecosystem management on public lands, relationships among forest health conditions, silvicultural options, and stand structures must be considered. It is evident that forest health problems can no longer be adequately handled at the stand level. Instead, these problems must be addressed at landscape scales that transcend traditional stand-level analyses.

In recent years, understanding of silviculture-forest health interactions has been identified as a major area of need in forestry research. For example, the publication *Forestry Research: A Mandate for Change* (National Research Council, 1990) identified alternative silvicultural systems and their relation to forest health concerns as a specific research need. The SAF task force report on forest health (1993) also points to the need for silvicultural strategies aimed at forest health problems. Additionally, the publication *Healthy Forests for America's Future - A*

Strategic Plan (USDA Forest Service, 1993) identifies goals and actions to protect forest health, including a specific recommendation to "develop pest modeling and decision support systems to assist land managers in making ecosystem management decisions." In discussion of the direction of future research, Swanson and Franklin (1991) state that "... models of alternative landscape patterns must be linked with analytical techniques, such as modeling, to evaluate the responses of key variables...". The project proposed herein addresses this need.

The inland forests of the Pacific Northwest have specific health conditions related to past disturbances and management practices that can be assessed through modeling. This project will investigate the interactions between biophysical conditions, stand structure, and forest health conditions, and determine silvicultural alternatives for meeting ecosystem management objectives for the Bitterroot Ecosystem Management/Research Project (Carlson and others, 1994). A decision support system for silviculturists and forest health specialists on the Bitterroot National Forest will be constructed and validated to predict the outcomes of silvicultural treatments in specific land types.

PREVIOUS WORK AND PRESENT OUTLOOK

Forest Health Conditions

The current condition of forests in the inland Northwest can be partially attributed to the exclusion of fire and past management activities (Mutch and others, 1993; Monnig and Byler, 1992). Seral species have been or are being replaced by species that are less resistant to regional insects and pathogens. The resulting forests are composed of different structures that may need modification to meet the objectives of ecosystem management, notably the maintenance of forest health (USDA Forest Service, 1992). Effects of silvicultural treatments on stand structure and forest health have been evaluated at the stand level in the past, and landscape level implications are beginning to be explored (Franklin and Forman, 1987; USDA Forest Service, 1994). The interior Douglas-fir habitat type has been reviewed for management alternatives directly related to forest health conditions (Byler and Zimmer-Grove, 1991). Byler and Zimmer-Grove provided recommendations for managing the current species composition to reduce the deleterious effects of insects and disease; notably western spruce

budworm, root disease, and dwarf mistletoes.

Probability models and rating systems exist for a number of major pests in the Pacific Northwest (Byler and others, 1990; Hawksworth, 1977; Shaw and Kile, 1991; Williams and Marsden, 1982). Data has been collected and interpreted for the population dynamics of western spruce budworm in the Pacific Northwest for the period 1959 to 1988 (Campbell, 1993). The Columbia River Basin Assessment Project is modeling interactions of insects and pathogens with stand structures on a coarse scale, and will be a useful reference in this project (Keane, 1994). The opportunity exists to apply these and other models to conditions occurring on the Bitterroot National Forest.

Stand Structure

Considerable information is available on stand structural development of forests in the Douglas-fir and grand fir climax series. In western Montana, O'Hara is the lead PI for an ongoing McIntire-Stennis project that is reconstructing stand development of Douglas-fir and grand fir climax series stands. Additional information is available from studies by Schmidt and others (1976) and other sources (*e.g.,* see Cobb and others, 1993 for summary) for similar forest types in western Montana and northern Idaho. Previous studies by Larson (1982, 1986), Cobb and others (1993), and O'Hara (1994) have described stand structural development of Douglas-fir and grand fir climax series on the Wenatchee National Forest. O'Hara is currently developing a structural classification system for the Columbia River Basin assessment. This system, along with work underway for the Bitterroot Ecosystem Management project (Pfister, 1994), will be used to classify stands in the proposed study.

Silvicultural Opportunities

Silvicultural manipulations provide a means to create structures that meet forest health objectives. References to efforts to link silviculture and forest health are too numerous to cite: However, a sampling of opportunities are available in Baumgartner and Mitchell (1984). It is generally accepted that structures that include stressed trees are prone to a variety of insect attacks (*e.g.,* bark beetles) (Amman and others, 1988). Some defoliators, such as the

western spruce budworm, are favored by multi-strata structures of susceptible species (Carlson and others, 1985; Carlson and Wulf, 1989). Most root pathogens are highly dependent upon species composition of stands. In most cases, silvicultural manipulations can reduce density and stress, modify vertical structure, or modify species composition to create stands less susceptible to these forest health problems.

Integration

Decision-making tools are available for integrating silviculture, stand structure, biophysical conditions, and forest health problems. For example, O'Hara and others (1990) developed an expert system for the eastern Washington Cascades to project stands through time and predict the need for silvicultural manipulations in the presence of forest health problems. However, this system used expert knowledge of linkages between forest health, structure, and silviculture and was unable to predict future forest health problems beyond the current knowledge of the practicing forest managers (experts). A second system for the Wenatchee National Forest has linked structural characteristics with the potential for differentiation (stand development without stagnation) (O'Hara and Oliver, 1992). This system assumed that a differentiating even-aged stand was more vigorous and less susceptible to most forest health problems than a stagnating stand; however, the link to actual forest health problems was indirect.

Mr. Jim Chew (USDA FS INT Research Station) is developing an expert system to project changes in landscape conditions over time. This system projects changes in structural development following different scenarios and allows land managers to anticipate large-scale changes in landscape patterns. Forest health problems are addressed in Chew's system, but no hard data is available on insect and pathogen occurrence in relation to biophysical environment, silvicultural history, and/or stand structure.

Additional components of the Bitterroot Ecosystem Management/Research Project that will be linked to this study include landscape analyses (Pfister, PI) and stand structure classification (Keane, PI).

OBJECTIVES

This project is designed to predict landscape patterns following silvicultural activities, given existing stand structures and forest health conditions. Probabilities of disturbance related to the landscape, site conditions, species distribution, and insect and pathogen populations will be incorporated. Specific objectives to be met are as follows:

1. Examine interactions between stand structures and forest health on specific land types;
2. Determine silvicultural alternatives for creating desired structures or to reduce or enhance forest health problems at stand and landscape scales;
3. Develop a decision support system to help land managers understand interactions (#1) and develop alternative silvicultural strategies (#2).

HYPOTHESIS

Primary hypothesis:

Forest health conditions are the predictable result of interactions between biophysical conditions, silviculture, and stand structure.

Secondary hypotheses:

1. Potential insect and pathogen problems can be linked to stand structural components.
2. Forest health conditions can be linked to biophysical conditions.
3. The probability of future insect and pathogen occurrence can be predicted for specific biophysical environments with known structural development patterns.
4. Silvicultural manipulations can be used to create structures to meet desired future forest health objectives.

PROCEDURES

Study Areas

The Stevensville West-Central planning area on the Bitterroot National Forest has been selected as the demonstration site (prototype) for hypotheses testing. Other study sites will be located in western Montana on Douglas-fir and grand fir climax series for model refinement and validation. The study will be replicated on the Wenatchee National Forest in

Washington. Specific land types within Douglas-fir and grand fir climax series with similar site conditions (*e.g.,* moisture regimes, elevation, slope, and aspect) will be selected using the USDA Forest Service ECODATA data base. Study areas in each structural stage will be evaluated within each land type.

Sampling Design

The sampling methodology presented by Arno and others (1993) will be used to establish a grid for evaluating stand structures and forest health conditions in Douglas-fir and grand fir climax series. Field data will be collected using a fixed plot (.025 ha) system in the selected areas. Two structural classification systems will be used (O'Hara and Pfister), and the following information will be collected: GPS coordinates; biophysical site characteristics; tree species; diameter; height; crown length; number of trees less than 4.5' tall and species; age structure; sapwood; presence of insects and pathogens; silvicultural history; fire history.

Probability Assessment

Three sources of information will be utilized to assess probabilities:

1. Existing studies and scientific opinion. Considerable literature has been published on forest insects and disease, but it has not been linked specifically to biophysical environments or structural classifications.
2. Broad scale sampling data.
3. Stand projection systems, such as: Prognosis, SPS, Structural Development Model (O'Hara), and the Columbia River Basin system (Keane, PI).

Forest health, silvicultural, and artificial intelligence systems experts will be involved in all phases of this project to provide advice and quality assurance/quality control.

Construction of Decision Support System

A variety of stand and landscape-level projection models are currently available. The Columbia River Basin Project (USDA Forest Service) will have a one-kilometer pixel scale model available within the timeframe of this project, which will be useful as a tool in designing

the proposed support system. Probability-based decision rules will be developed to integrate forest health, structural and biophysical conditions. The SIMPPLLE model, designed to project vegetation development, will also serve in a base and supporting capacity.

PROBABLE DURATION

This study is proposed for a two and a half-year period, from January 1, 1995, to June 30, 1997, with the following tentative schedule:

	1994	1995			1996			1997	
	3	1	2	3	1	2	3	1	2
Preparatory work	xxxxxxx				xxxx				
Fieldwork			xxxx			xxxx			
Data analysis				xxxxxxxx			xxxxxxxx		
Decision support system							xxxxxxxx		
Writing/publication							xxxxxxxxxxxxxx		

The proposed research will provide the following:

1. Landscape-level analyses of interactions between biophysical conditions, stand structures, and insect and pathogen problems. These will be replicated in two separate but similar ecosystems;
2. A decision support system that will provide more efficient decision making in situations where insect and pathogen problems exist or potentially exist;
3. Descriptions of silvicultural opportunities to direct stand development towards structures that are more resistant to insects and pathogens.

FINANCIAL SUPPORT

The USDA Forest Service funds include Bitterroot EMRP and PNW contributions.

ITEM	McSten FY95	USFS FY95	McSten FY96	USFS FY96	McSten FY97	USFS FY97	McSten Total	USFS Total	**Grand Total**
Faculty salary	1842	2760	1842	2760	1842	2760	5526	8280	$13,806
Research Assistant									
3/4 fall		4098		4098		4098	0	12294	$12,294
spring	5464		5464		5464		16392	0	$16,392
summer	5012		5012		5012		15036	0	$15,036
1/4 fall		1366		1366		1366	0	4098	$4,098
Total RA	10476	5464	10476	5464	10476	5464	31428	16392	$47,820
Hourly		8000		8000		8000	0	24000	$24,000
TOTAL SALARY	12318	16224	12318	16224	12318	16224	36954	48672	$85,626
Fac. ben. (23.5%)	432.87	648.6	432.87	648.6	432.87	648.6	1298.61	1945.8	$3,244
RA ben. (1%)	104.76	54.64	104.76	54.64	104.76	54.64	314.28	163.92	$478
Hourly ben. (11%)	0	880	0	880	0	880	0	2640	$2,640
TOTAL BENEFITS	537.63	1583.24	537.63	1583.24	537.63	1583.24	1612.89	4749.72	$6,363
Supplies	700	1500	700	1500	700	1500	2100	4500	$6,600
Equipment		4000					0	4000	$4,000
Travel	1200	7000	1200	7000	1200	7000	3600	21000	$24,600
Publication costs						3000	0	3000	$3,000
TOTAL DIRECT	$14,756	$30,307	$14,756	$26,307	$14,756	$29,307	$44,267	$85,922	**$130,189**

Budget Justification

Funding for the proposed project will come from three sources to support the analysis of both study areas. The PNW Research Station has committed $20,000 per year for three years for the Washington Cascade segment of study. Approximately $44,000 has been requested from the University of Montana's McIntire-Stennis program. McIntire-Stennis funds will be combined with funding from the Bitterroot Ecosystem Management project to complete the western Montana segment of study. Greater funding is required for the western Montana segment because methodology will be developed and tested in Montana before application in Washington. The total non-McIntire-Stennis budget is less than $90,000 to allow for inflation.

PERSONNEL

Dr. Kevin O'Hara, Associate Professor of Silviculture

Ms. Elizabeth Brantley, Graduate Student, M.F. Forest Pathology

Dr. Paul Hessburg, Plant Pathologist, Region 6, USDA Forest Service

Dr. Jim Byler, Supervisory Plant Pathologist, Forest Pest Management, Region 1, USDA Forest Service

INSTITUTIONAL UNITS INVOLVED AND COOPERATION

- This project will be undertaken by the aforementioned faculty and graduate student of the School of Forestry, University of Montana, Missoula, MT.
- The USDA Forest Service Pacific Northwest Experiment Station has also agreed to support this project with expertise and financial contributions (Paul Hessburg).
- The USDA Forest Service Intermountain Experiment Station will provide data and assistance with assessment.
- Regions 1 and 6 of the USDA Forest Service will provide knowledge and expertise in the population dynamics of major insects and diseases (Dr. Jim Byler, Couer d'Alene, ID; Dr. Susan Hagle, Missoula, MT).

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A 6800 YEAR VEGETATION AND FIRE HISTORY IN THE BITTERROOT MOUNTAIN RANGE, MONTANA

By

ANNE ELIZABETH KARSIAN

Presented in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

UNIVERSITY OF MONTANA
Department of Forestry

1995

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INTRODUCTION

A common misconception is to regard landscapes as balanced, steady state communities defined by specific structures, functional processes and species composition (Tausch *et al.*, 1993). This vision is perpetuated in popular culture with images of majestic "old growth" forests in movies, literature and the evening news. One potential origin of this thought in the research community can be found in Clements' theory of climax vegetation. Here, plant associations are viewed as discrete complexes which arise, grow, mature, and die through predictable biological steps of organization (Clements, 1916). The antithesis of this theory is well grounded in Gleason's hypothesis on the individualistic response of plant communities (Gleason, 1926). Each plant adjusts independently to biotic and abiotic changes in their environment.

The paleoevironmental record adds further credence to Gleason's hypothesis by tracing plant communities as transient assemblages of varying species composition through time (Davis, 1981; Mehringer, 1985; Brubaker, 1988; Schoonmaker and Foster, 1991). Pollen studies have illustrated that each plant species has a different history since the retreat of the glaciers (Davis, 1969). As an example, several researchers have determined that Tsuga heterophylla (western hemlock) (a species that is well established in the ~~area~~ northern e m today) did not appear in northern Idaho until approximately 2000 years ago (Mack *et al.*, 1978; Mehringer, personal communication). Current ecological research tends to favor the individualist response of communities. Yet, there is an apparent lag time between the rise of a new scientific theory, and its recognition by the general populace.

Pollen analysis provides a description of vegetation history. Further conclusions regarding causal relationships are tenuous. However, by knowing which plants were present, the ecological framework of the constituents in the plant communities and their relative abundance, conclusions can be made concerning the climate and vegetation dynamics present at the time the pollen was deposited (Faegri and Iversen, 1989). The power of pollen analysis originates in its ability to identify the dominant vegetation on the landscape; this knowledge suggests general climatic factors affecting vegetation based on modern pollen assemblages (Davis, 1969).

In the current age of conducting thorough broad scale analyses of landscapes, a view of past vegetation associations and ecological processes could aid in an understanding of the variety of pathways which resulted in the current landscape mosaics (Hann, 1989). As ecologists and land managers strive to understand forest structural patterns occurring today, it has become increasingly evident how fractured the picture is without an understanding of the past.

> "One striking result of the study is a realization that little evidence of the prior vegetation, including the original forest, or past land-use is apparent in the modern landscape... This great deceptiveness in the appearance of the forest to the modern investigator highlights the utility of diverse approaches to understanding and characterizing forest communities." (Foster *et al.*, 1992).

An elucidation of vegetation change through time can be used to view the processes that may have contributed to the present mosaic of plant communities across the landscape. Investigations using pollen analysis range from constructing the vegetation history of an entire region to reconstructing

the biological history of a particular plant species (Faegri and Iversen, 1989). In the northern Rocky Mountains, the focus of pollen studies has been primarily on the reconstruction of vegetation communities and climate change, (Waddington and Wright, 1974; Davis *et al.*, 1977; Mack *et al.*, 1978, 1983; Barnosky, 1989; Barnosky *et al.*, 1987) , or the characterization of fire regimes (Mehringer, Arno and Petersen, 1977; Smith, 1983; Hemphill, 1983; Onken, 1984).

This study is a 6800 year characterization of the change in vegetation and fire history at Mary's Frog Pond in the Bitterroot Mountain Range of western Montana. This information comes from the description of plant associations revealed in the pollen assemblages. The record contributes to the sparse, but growing number of places in the interior Pacific Northwest where detailed pollen studies have been completed (for a review see Mehringer, 1985). The resulting paleoecological description will serve as an illustration of how past vegetation communities and ecological processes have evolved. As the long term history of each new site is interpreted, more precise inferences can be made of the ecological amplitudes which shaped regional landscapes of the past.

OBJECTIVES

The following objectives have been established for the analysis of sediment samples from Mary's Frog Pond:

1. describe the shifting vegetation assemblages through the use of microfossils;

2. reconstruct fire history of the area through charcoal influx;

3. compare the resulting vegetation and fire history with similar studies in the region.

LITERATURE REVIEW

Pollen and Fire History Studies

The first efforts towards reconstructing past vegetation communities in this region were forged by palynologist Henry P. Hansen in the 1940's. His studies took him from Oregon up through Washington, across northern Idaho and into western Montana. Specific sites Hansen studied in the region surrounding Mary's Frog Pond include Bonners Ferry (Hansen, 1943) and Hagar Pond (Hansen, 1939) in north Idaho plus Fish Lake and Johns Lake in Glacier National Park (Hansen, 1948). Since Hansen's efforts, a few additional endeavors to reconstruct past environments (cited above) have occurred, but in general the region encompassing northern Idaho and western Montana is a research void waiting to be unlocked.

Pollen and charcoal analysis of three sites have been conducted in the same general geographical area as Mary's Frog Pond. They include Sheep Mountain Bog in the Rattlesnake Mountains (Hemphill, 1983), Lost Trail Pass Bog in the Bitterroot Mountains (Mehringer, Arno and Petersen, 1977) and Smeads Bench Bog in the Cabinet Mountains (Chatters and Leavell, 1994). At each locality both the fossil pollen and charcoal have been analyzed to extrapolate the vegetation change and fire history of the surrounding area. Each site contributes some illuminating element that adds to the overall picture of the paleoenvironmental history of the region.

Sheep Mountain Bog developed in a small cirque at an elevation of 1920 meters. The analysis examined fire frequency by looking at microscopic

charcoal, the ratio of charcoal to pollen and tree fire scars from the immediate area. Hemphill (1983) found that between 7000 and 2000 yr B.P., the fire frequency gradually decreased. After 2000 yr, B.P., the number of fires increased, however since 1100 yr B.P., the superabundance of charcoal is unprecedented in the last 12,000 years. This dramatic increase is attributed to human land use influences rather than climatic change.

Lost Trail Pass Bog, at an elevation of 2152 meters, suggests that a sagebrush steppe community dominated the landscape just after the retreat of glacial ice 12,000 years ago (Mehringer, Arno and Petersen, 1977). Pines [thought to be Pinus albicaulis (whitebark pine)] soon replace the steppe suggesting cooler climatic conditions for the 3000 to 4000 years of their dominance. Pseudotsuga menziesii (Douglas-fir) and a different group of pines [this time thought to be Pinus contorta (lodgepole pine)] replace the whitebark pine, and charcoal abundance increases. By 4000 yr B.P., the Douglas-fir is no longer prevalent in the pollen assemblage and the pines dominate. As with Sheep Mountain Bog, the fire frequency shows a dramatic increase during the last 2000 yr B.P. This is again attributed to human influence on the landscape.

Smeads Bench Bog provides an analysis of a plant community at a lower elevation (1190 meters) in a moist forest type (Chatters and Leavell, 1994). The hemlock forest (Tsuga heterophylla) present around the bog today is a relatively recent forest type originating only about 2000 years ago. The results from this study are specifically designed as recommendations to land managers making multiple land use decision on public lands. This reflects the current trend of conducting large scale ecological analysis of forested lands.

Use of Microscopic Charcoal for Interpreting Fire History

The fire history in context with the pollen record provides a multidimensional understanding of the interactions between disturbances and vegetation dynamics. Studies of microscopic charcoal have been directed towards the effects of fire on plant communities (Swain, 1981; Green, 1981) or the effects of human disturbances (Hemphill, 1983; Mehringer, Arno and Petersen, 1977; Smith, 1983). These studies clearly illustrate the potential use of microscopic charcoal for identifying the general effects of fire on vegetation. Fire is a part of the ecosystem and may be ~~some~~ an indicator of stress. The pollen record provides a context of what is happening in the plant community. Thus, the pollen and charcoal record together can provide insight into a critical ecosystem interaction.

Fire history can be reconstructed through microscopic charcoal deposited in lake sediments. However, limitations of this technique must be acknowledged to qualify the resulting data. The amount of charcoal in a sample is not only influenced by how much was originally produced, but also by dispersal and deposition rate, preservation in the sediments, sampling techniques, laboratory preparation and counting methods (Patterson *et al.*, 1987). Patterson *et al.* (1987) warns that varying placement and frequency of samples extracted from the sediment core can lead to different fire histories, and even lead to non-existent fire regimes. Clark (1988) argues that a tight chronology of the sediments is essential for a reliable reconstruction of local fires; preferable the chronology provided from annually laminated sediments.

Despite the potential problems with reconstructing fire histories through microscopic charcoal in less than perfect conditions, the technique can still provide good overviews of general trends. At Sheep Mountain Bog (Hemphill, 1983) and Lost Trail Pass Bog (Mehringer, Arno and Petersen, 1977), an uncontested increase in charcoal since the last 2000 yr B.P. suggests an increase in fires attributed to human land use rather than climatic change. Working with varved sediments in northern United States, Swain (1978) has illustrated broad regional patterns concerning the effects of fire on vegetation communities.

In order to interpret the microscopic charcoal at Mary's Frog Pond, a ratio of charcoal to total terrestrial pollen was calculated. Charcoal to pollen ratios tend to eliminate false peaks in the data since pollen should be redeposited along with the charcoal. Yet, immediately after a real fire, the amount of charcoal will be higher than the pollen because of the superabundance of airborne charcoal and the reduction of the pollen source (Swain, 1973). Swain (1973) considered the ratio of charcoal to pollen from Lake of the Clouds, Minnesota, the best indication of actual fires. If charcoal and pollen are transported and deposited similarly, one would expect more charcoal in relation to pollen following a fire than during times without fires. Comparing peaks of more charcoal to pollen may give an indication of individual fires (in laminated sediments) and provide a sequence of fires throughout the pollen core. Still, with redeposition, sediment mixing and delayed charcoal transportation, charcoal peaks from a single fire can span a decade or more (Patterson *et al.*, 1987).

STUDY AREA

Mary's Frog Pond is situated on a north facing slope at an elevation of 1753 meters in the Bitterroot Mountain Range in western Montana. The pond is on the Lolo National Forest, T39N, R22W Sections 15 and 22 (Figure 1). The surface area of Mary's Frog Pond is relatively small (approximately 60 m x 200 m) and was formed by retreating ice leaving a recessional moraine in a deep, steep-sided canyon. Although the pond is approximately six meters deep, suspended sediments prevent light from penetrating over three meters.

Mary's Frog Pond is presently surrounded by an Abies lasiocarpa forest habitat type (Pfister *et al.*, 1977). A nearly pure stand of fire generated Pinus contorta with some Larix occidentalis encompasses the perimeter of the pond. A recent history of severe fires has been compiled by Stephen F. Arno of the Intermountain Fire Science Lab in Missoula, Montana (Appendix B). Severe fires in 1805 and 1889 are dated from fire scars. The earliest fires are extrapolated from the age of surviving shade-intolerant trees (Larix occidentalis and Pinus contorta). Most of the present-day Larix occidentalis and Pinus contorta at the site became established soon after the 1889 fire.

METHODS

Data Collection

Sediment cores were collected from Mary's Frog Pond in August and November of 1985 in a cooperative agreement between Washington State University, Pullman, WA and the U. S. Forest Service. Sediments from the center of the pond were recovered with a modified Livingston piston corer and drive tower supported by a plywood raft (Cushing and Wright, 1965). The cores barrels are made of a 10 cm (4 inch) diameter PVC pipe. Two cores from the center of the pond were used for this study: one from a depth of 0.00

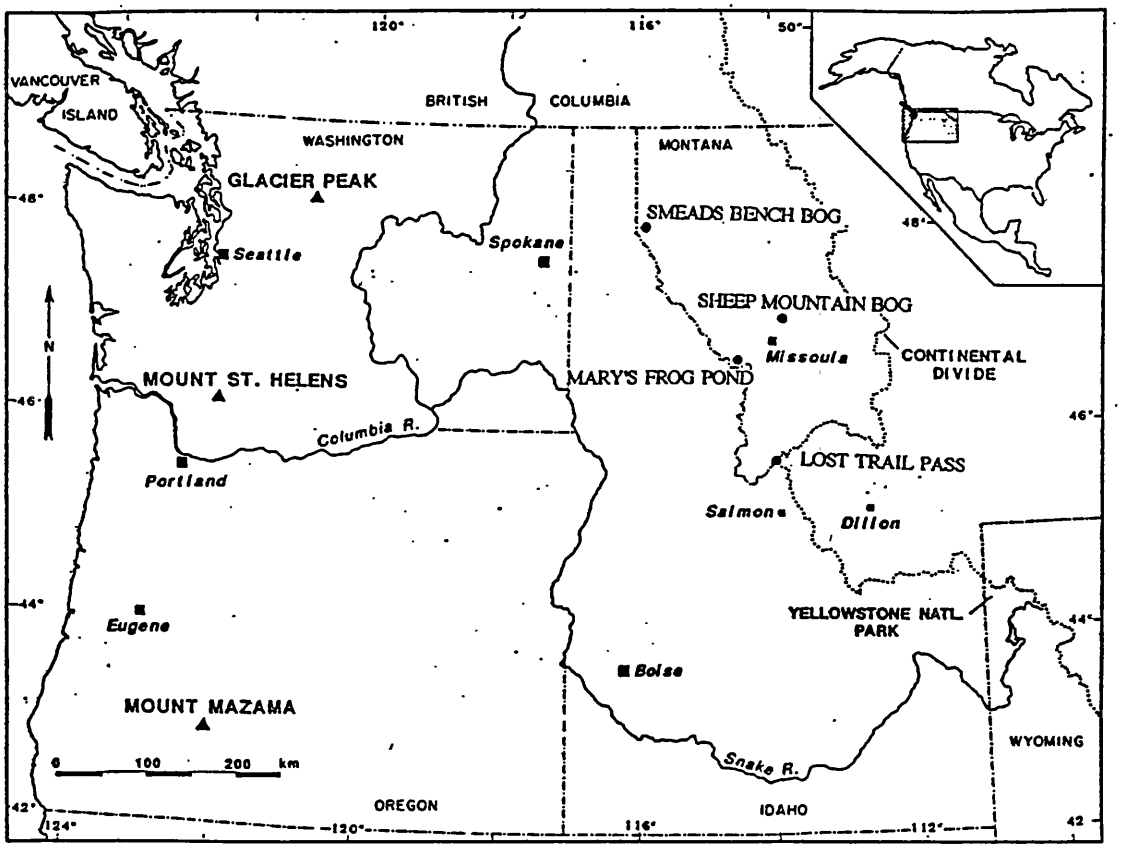

Figure 1. Map showing the location of Mary's Frog Pond and three other sites discussed in the text. •, coring sites; ▲, Cascade volcanoes; ■, cities and towns (adapted from Foit *et al.*, 1993).

m to 1.46 m and the second from 0.35 m to 2.05 m. Overlapping cores were taken to ensure an uninterrupted record within the solidified sediments.

The sediments were exposed for cleaning and sampling by splitting the core barrels lengthwise with a circular saw. The cores reveled two volcanic ash lenses which are used as marker dates in the Pacific Northwest; Mazama and Glacier Peak ash. Paired samples were taken by packing sediment into a 0.5 teaspoon scoops equaling a volume of 2.3 cm^3 (Fletcher and Clapham, 1974). Samples were extracted every five centimeters from the two adjacent overlapping cores to attain a continuous pollen record from the most recent sediment deposits to the fall of Mazama ash (the time period of interest). Sixty centimeters of the top most core were sampled with an additional 125 centimeters coming from the deeper core. A total of 46 samples were extracted (thirteen from the top most core and thirty-three from the deeper core). This allows for an overlap of thirty-five centimeters with which to correlate the two cores and attain an uninterrupted pollen record from the fall of Mazama ash to the top of the sediment core.

One of each pair of extracted samples was used to determine percentage organic carbon by weight loss on ignition. The dry weight of the samples was reported, then each was burned at 600° C for at least 24 hours, cooled in a desiccator, and weighed on a Mettler balance. The resulting weight loss gives a measure of organic carbon in the sediment samples (Dean, 1974).

The concentration estimates of pollen and charcoal per cubic centimeter were determined through adding a known quantity of Lycopodium spores to the sample (10,850 ± 200 in each of 20 tablets, Batch 006720 for samples 1-16; 13,911 ± 308 in each of 10 tables, Batch 710961 for samples 46-75) (Davis 1969; Stockmarr 1971). The samples were deflocculated in distilled water and mixed with weak HCl on magnetic vortex mixers. The

samples were washed through 100 mesh per inch screen to remove extraneous debris. Calcium carbonates, humic acids, siliceous matter and cellulose were removed with additional HCl, KOH treatment, HF and acetolysis. The samples were stained with Safrinin O, and mounted in 2000 cs silicon oil (Faegri and Iversen, 1989).

In order to determine the sequence of ecological changes through time, a chronological framework is established through radiocarbon dates taken from organic fossils found within the core samples. A preliminary time scale can often be determined in the Pacific Northwest through volcanic ash lenses. The cores from Mary's Frog Pond have a thick band of Mazama ash that has been dated to 6850 B. P. (Bacon, 1983). To further refine the chronology of the pollen core, nine macrofossil samples were removed from the sediments to be used as accelerator radiocarbon dates. These included six Pinus contorta needles, one sample of Sphagnum sp., Nuphar sp. seeds and a large charcoal fragment. The samples were dated by the Institute of Arctic and Alpine Research, Laboratory for Accelerator Radiocarbon Research at the University of Colorado, Boulder.

The two overlapping cores were correlated to one another through visual inspection of the sediments, radiocarbon dates and using the resulting pollen diagrams. As a result, the top of Locality II Core I Drive I is considered zero centimeters (the top of the pond sediments) and the bottom of Locality I Core I Drive I is 190 cm below surface with the contact of Mazama tephra. All thirteen of the samples from Locality II Core I Drive I were used. The top seven samples from Locality I Core I Drive I were not used since they are a part of the overlap of the cores. The results and discussion that follow will consider the two combined cores as a single record of thirty-nine samples (Figure 2).

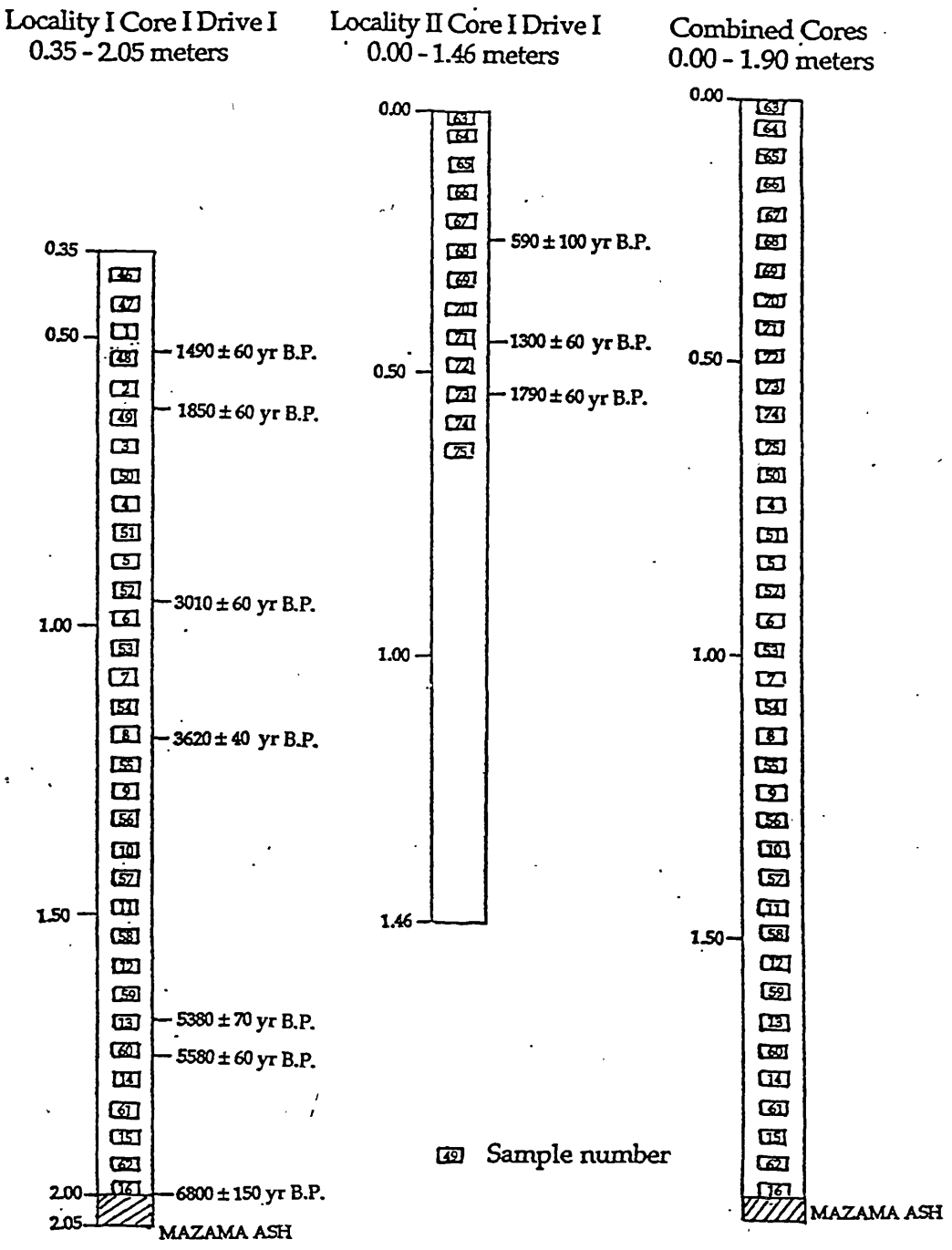

Figure 2. Illustration of how the two sediment cores were sampled and combined to create one continous record. Dates along the length of the cores correspond to the ^{14}C ages obtained from macrofossils found within the sediments.

Pollen and Data Analysis

At least 500 terrestrial pollen grains were counted for each of the 46 samples at 400X magnification. Spores, acid-resistant algae and charcoal fragments were also tallied. Pollen and spore identifications were confirmed by comparison with the pollen reference collection at Washington State University. Charcoal fragments were counted and measured along the longest axis in three size classes; 25-50μm, 50-100μm, and >100 μm, following Mehringer, Arno and Petersen, 1977.

Absolute pollen counts were entered into a spread sheet program to generate a relative frequency pollen diagram. The resulting pollen diagram contains all the identified taxa organized by arboreal species, shrubs, forbs, aquatic plants, spores, and algae (Appendix A). A second percentage pollen diagram of the most common taxa is presented to facilitate interpretation of the results (Figure 3). Other pollen diagrams include ratios of nonarboreal pollen (NAP) to arboreal pollen (AP), ratios and percentage diagrams of specific conifers, and pollen accumulation rates per centimeter squared per year.

Four pollen zones were delineated using psimpoll 2.23 (Bennett, 1994), a pollen data analysis computer program. The program divides the zones by agglomeration using constrained cluster analysis developed by Grimm (1986). This method is based on the constraint that the data must be clustered by stratigraphically adjacent samples. Four ubiquitous taxa, Pinus, Alnus, Botryoccus and Scenedesmus were removed from the data set for zonation purposes. These four taxa have a large ecological amplitude and only serve to over shadow those species that might better delineate specific zones.

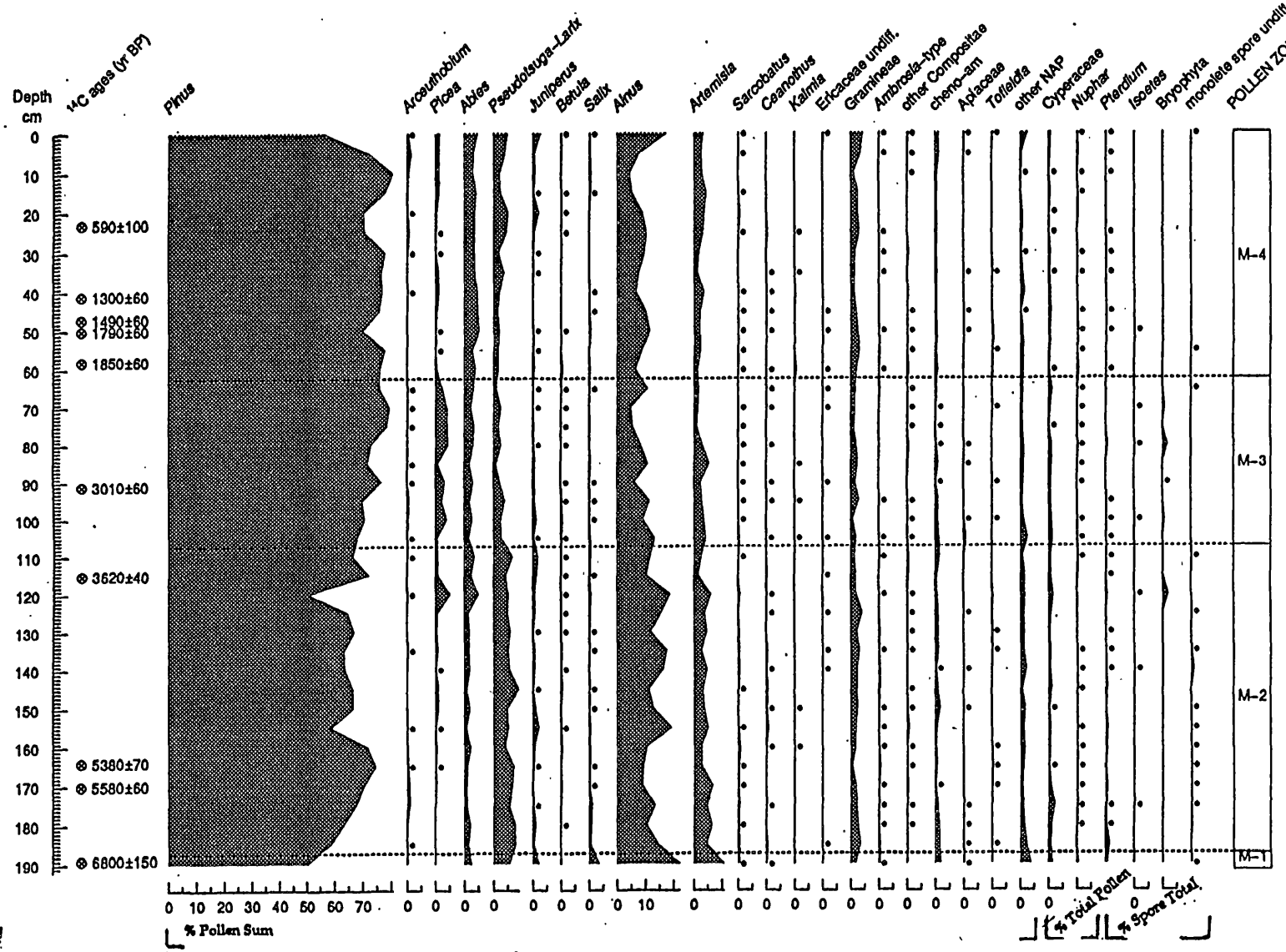

Figure 3. Relative percentage diagram of selected pollen and spore taxa from Mary's Frog Pond, Bitterroot Mountains, Montana. • = <0.5%.

Total pollen and charcoal accumulation rates were calculated for Mary's Frog Pond sediments. Pollen and charcoal accumulation rates estimate the annual deposition of the taxon independent of all other pollen types and varying sedimentation rates (Davis, 1969; Birks and Gordon, 1985). The concentration of the indigenous pollen is estimated in proportion to the number of Lycopodium counted.

Microscopic charcoal is analyzed through ratios of charcoal to total terrestrial pollen and charcoal accumulation rates per centimeter squared per year. The accumulation rate of the three charcoal size classes referenced above are separated to try and accentuate any differences in fire history through time.

RESULTS

Sediments and Chronology

Radiocarbon dates range from 590 ± 100 yr B.P. at 23 cm, to 5580 ±60 yr B.P. at 170 cm. The base of the core is considered 6800 ±150 yr B.P. based on the accepted age of Mazama ash at 6850 ± 150 yr B.P. (Bacon, 1983). In order to determine sedimentation rate from the base of the core to the present, the radiocarbon dates were "calibrated" to accommodate temporal variations in the radiocarbon content of atmospheric carbon dioxide (Stuiver and Reimer 1993). Table 1 shows the ^{14}C dates attained from macrofossils in the core, their respective depths, source, and the calibrated dates. The "calibrated" radiocarbon dates were used to determine sedimentation rate only. A graph plotting depth to age of both "conventional" and "calibrated" radiocarbon dates shows that the deposition rate of the sediments was relatively constant throughout the length of the core (Figure 4).

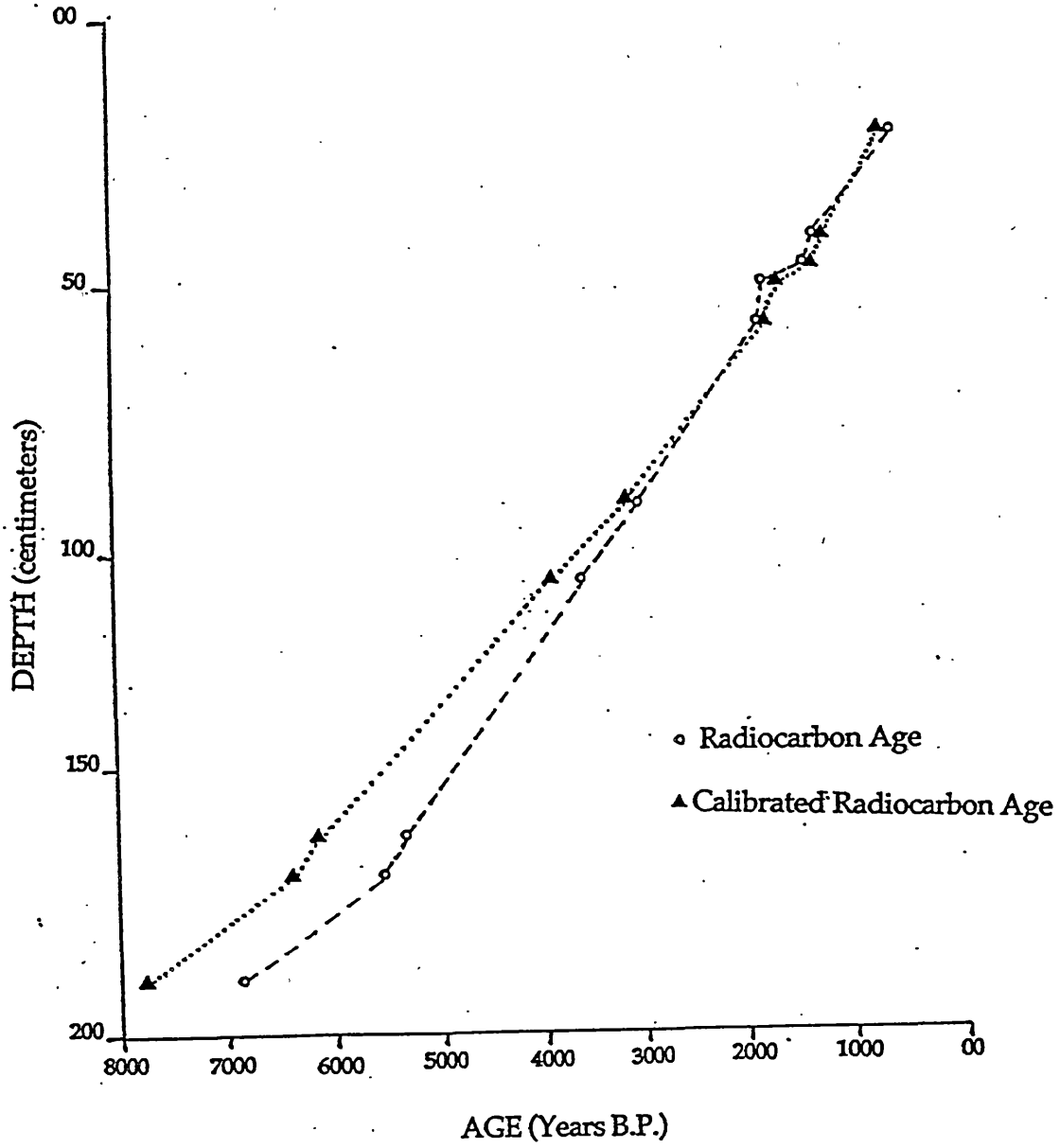

Figure 4. Distribution of radiocarbon dates and their calibrated radiocarbon age (Table 1) for 190 centimeters of the Mary's Frog Pond cores above Mazama ash. The radiocarbon dates are derived from macrofossils extracted from the sediment cores. The calibrated radiocarbon dates are attained from Stuiver and Reimer, 1993 (see text).

DEPTH	^{14}C AGE YR B.P.	MATERIAL DATED	CALIBRATED ^{14}C DATE
23 centimeters	590 ± 100 yr B.P.	*Nuphar* spp. seeds	618 yr B.P.
41 centimeters	1300 ± 60 yr B.P.	*Pinus contorta* needle	1259 yr B.P.
47 centimeters	1490 ± 60 yr B.P.	*Pinus contorta* needle	1366 yr B.P.
50 centimeters	1790 ± 60 yr B.P.	*Sphagnum* spp.	1706 yr B.P.
58 centimeters	1850 ± 60 yr B.P.	*Pinus contorta* needle	1815 yr B.P.
91 centimeters	3010 ± 60 yr B.P.	Charcoal fragment	3205 yr B.P.
115 centimeters	3620 ± 40 yr B.P.	*Pinus contorta* needle	3955 yr B.P.
164 centimeters	5380 ± 70 yr B.P.	*Pinus contorta* needle	6264 yr B.P.
170 centimeters	5580 ± 60 yr B.P.	*Pinus contorta* needle	6397 yr B.P.
190 centimeters	6800 ± 150 yr B.P.	Mazama ash	7604 yr B.P.

Table 1. Mary's Frog Pond radiocarbon dates.

The percent organic content of the sediment (measured by weight per volume of sediment) is greatest above 30 cm depth and gradually declines below that point (Figure 5). Two samples mark a dramatic contrast to the diagram at 105 cm and 125 cm. The percent organic content drops from 36% to 20 % and 34% to 20% respectively. These declines in organic content correspond with a tremendous increase in charcoal accumulation.

Relative Frequency Diagram

Figure 3 displays the relative frequencies of the most common pollen, spores and acid resistant algae in the analyzed sediment core from Mary's Frog Pond (a complete percentage diagram is found in Appendix A). The relative frequency of the taxa is calculated as follows: "pollen sum" includes all terrestrial pollen excluding Cyperaceae (sedge family), "total pollen" indicates the percent of all terrestrial pollen, Cyperaceae and aquatic plants, "spore total" adds spores to the terrestrial and aquatic taxa, and "microfossil total" encompasses all pollen, spores and acid resistant algae. The division of taxa into these various totals places the primary interest on regional vegetation. Pollen that originated from the upland vegetation are therefore

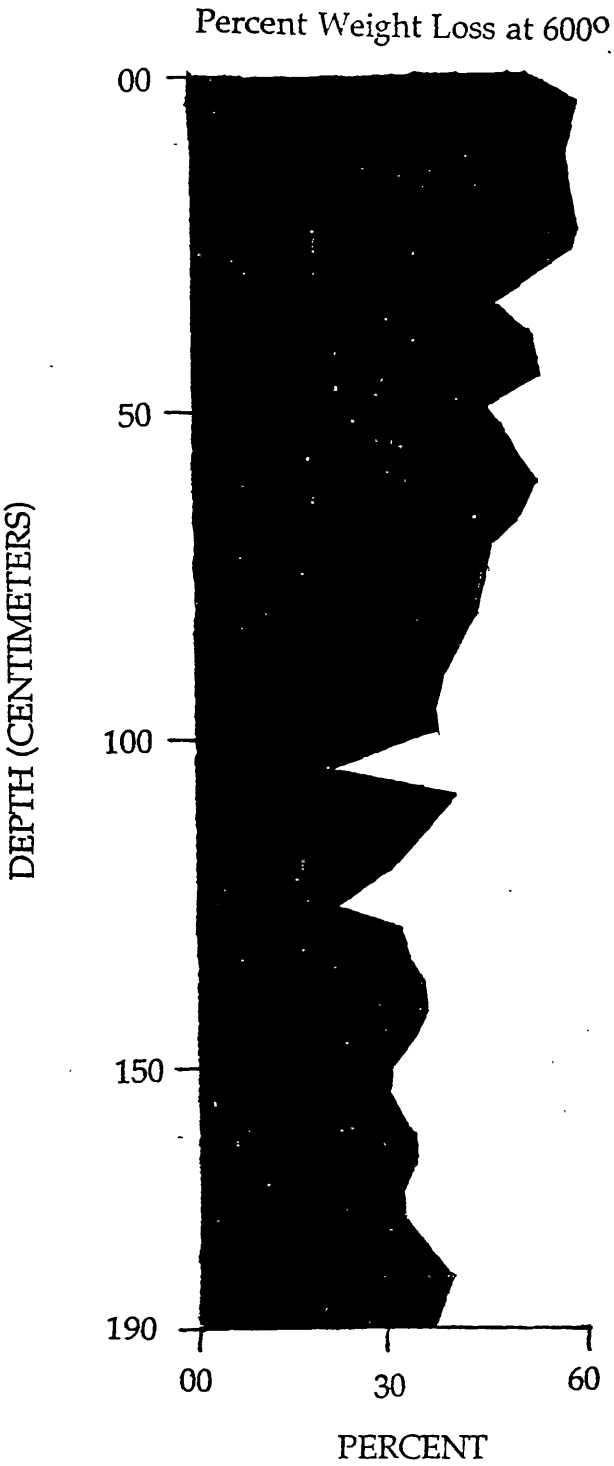

Figure 5. Percent organic carbon in samples after combustion at 600° C. Two dips at 105 cm and 125 cm correspond with a sharp increase in the relative abundance of microscopic charcoal.

included in the pollen sum. Birks and Gordon (1985) suggests that local lowland aquatic vegetation be excluded for they are site specific and represent a different vegetation from the primary objectives of this study. A dot on the diagram represents a relative frequency of less than 0.5%.

Terrestrial pollen

Pinus (pine) pollen dominates the relative frequency diagram representing up to 80% of the terrestrial grains in the recent portion of the sediment core. A distinction between diploxylon (P. contorta and P. ponderosa) and haploxylon (P. albicaulis, P. monticola, P. flexilis) pine was made when possible. Diploxylon grains dominate haploxylon consistently throughout the pollen record (Figure 6).

Other conifers includes Picea (spruce), Abies (fir), Tsuga heterophylla, Tsuga mertensiana (mountain hemlock) and Pseudotsuga-Larix (Douglas-fir, larch). Pseudotsuga and Larix are grouped as one taxa since the pollen grains are not morphologically distinct enough from one another to be separated. Larix occidentalis is a significant component of the stands surrounding Mary's Frog Pond today. Still, Pseudotsuga is a common contributor to the elevation and habitat type of the immediate area (Pfister *et al.*, 1977). Consequently, it is difficult to speculate which of the taxon the pollen counts are more likely to represent.

Picea and Abies show a general trend towards gradually increasing in frequency as the sediments approach the present. The two species start to reach their maximum frequency about 2000 yr B.P. Picea first appears in the pollen record at a depth of 180 cm, corresponding to approximately 5800 yr B.P. Pseudotsuga-Larix exhibits the opposite trend with its greatest frequency occurring at the deepest part of the core between 110 cm to 190 cm (3500 yr B.P.

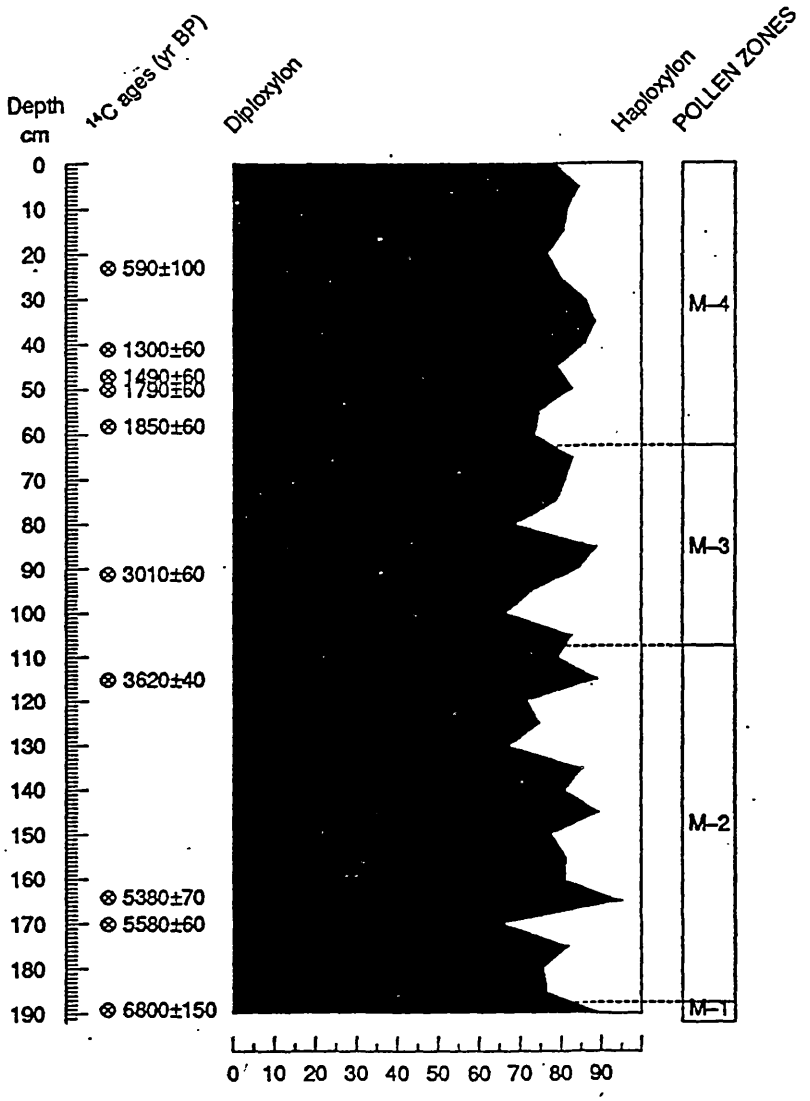

Figure 6. Relative percent of diploxylon to haploxylon pine pollen at Mary's Frog Pond, Montana.

to 6800 yr B.P.). Tsuga heterophylla occurs four times in the pollen record at depths of 15 cm, 35 cm, 40 cm and 45 cm while Tsuga mertensiana occurs once at a depth of 70 cm. Paralleling other pollen studies which contain Tsuga heterophylla, the species does not appear in this record until after 2000 yr B.P. (Chatters and Leavell, 1994, Mack *et al.*, 1978a). In each case, the Tsuga represents less than 0.5% of the total terrestrial pollen.

The greatest representation of shrub species is by Alnus and Artemisia. Alnus is a prolific pollen producer averaging approximately 10% of the total terrestrial pollen and never dips below 5% of the pollen sum throughout the length of the core. Artemisia remains a constant background component of the vegetation as it is an important taxa from lower elevations and blows in from other regions. Both of these taxa reached their highest percentage at the base of the core: Alnus at 22% and Artemisia at 11%.

Juniperus, Betula, Ceanothus and Salix all occur with some regularity, but rarely represent more than 0.5% of the total pollen. Other shrub species that are present sporadically include Kalmia, Vaccinium, Spirea, Holodiscus, Acer, Prunus, Berberis, and Ribes.

Gramineae and Cheonpodiineae (cheno-ams) are two additional taxa which appear with some frequency throughout the pollen diagram. Gramineae averages approximately 2% of the relative pollen frequency with its highest occurrence soon after Mazama ash at 4%. Chenopodiineae is often present at about 1% with its highest showing of 2% at the base of the core. Both families are rather prolific pollen producers and can disperse pollen over great distances. At least four grass species are currently present at Mary's Frog Pond.

The pollen record from Mary's Frog Pond contains a wide assortment of forbs throughout the core. Many of these are insect pollinated plants

which indicate a close proximity of these taxa to the site. The following genus and family are present: Compositae, Ranunculus, Primulaceae, Saxifragaceae, Ericaceae, Thalictorum, Cruciferae, Erigonum, Umbelliferae, Liliaceae, Tofieldia, Phacelia, Leguminosae, and Labiatae. At least two species of Compositae and Umbelliferae, three species of Rosaceae and eleven species of Ericaceae are present at the pond today (Table 2). Ephedra virdis is transported over long distances from the west and south and its pollen is present in three of the samples counted.

Aquatics

The aquatics include mire vegetation, i.e. obligate aquatic plants and bog and fen species. At Mary's Frog Pond these include Cyperaceae, Nuphar, Typha latifolia, Menyanthes, Drosera, Potemogeton and Scheuchizeria. Cyperaceae averages 1% of the pollen frequency consistently throughout the pollen core. Nuphar occurs with regularity (at less than 0.5%) along the length of the pollen record except for a distinct absence between 120 and 135 cm depth (approximately 3800 yr B.P. to 4300 yr B.P.). This break in Nuphar coincides with a tremendous increase in microscopic charcoal accumulations. The abundance of aquatic pollen grains, including members of the Cyperaceae family, are often indicators of fluctuating water levels.

Spores

The spores are represented by ferns, mosses, horsetail and mistletoe. Pterdium, Arthyrium, Cystopteris, and Dryopteris spores occur periodically with Pterdium being the most common of the ferns. Bryophyta (mosses) are not present in the pollen record until 120 cm depth (3800 yr B.P.) at which point they reach a peak of 2% of the spore total. Equisetum (horsetail) occurs

TREES	COMMON NAMES
Abies lasiocarpa	subalpine fir
Larix occidentalis	western larch
Picea spp.	spruce
Pinus contorta	lodgepole pine
SHRUBS	
Alnus sinuata	sitka alder
Kalmia microphylla	small-leaved laurel
Ledum glandulosum	labrador-tea
Linnaea borealis	twinflower
Lonicera utahensis	Utah honeysuckle
Menziesia ferruginea	fool's huckleberry
Rubus parviflorus	thimbleberry
Spiraea densiflora	subalpine spiraea
Vaccinium globulare	globe huckleberry
Vaccinium myrtillus	dwarf huckleberry
Vaccinium occidentale	western huckleberry
GRAMINOIDS	
Agrostis scabra	tickle-grass
Alopecurus aequalis	short-awn foxtail
Calamagrostis canadensis	bluejoint reedgrass
Carex canescens	gray sedge
Carex disperma	soft-leaved sedge
Carex lenticularis	lentil-fruited sedge
Carex limosa	mud sedge
Carex rostrata	beaked sedge
Carex scopulorum	Rocky Mountain sedge
Eleocharis palustris	common spikesedge
Eriophorum chamissonis	Chamisso's cotton-grass
Juncus ensifolius	dagger-leaf sedge
Glyceria borealis	northern mannagrass
Glyceria striata	fowl mannagrass
Luzula parviflora	small-flowered woodrush

FORBS	COMMON NAMES
Chimaphila umbellata	common prince's pine
Cicuta douglasii	douglas water-hemlock
Dodecatheon jeffreyi	Jeffrey's shooting star
Drosera rotundifolia	roundleaf sundew
Goodyera oblongifolia	rattlesnake plantain
Habenaria saccata	slender bog-orchid
Hieracium albiflorum	white-flower hawkweed
Hypopitys monotropa	pinesap
Ligusticum spp.	lovage
Listera cordata	heart-leaf twayblade
Menyanthes trifoliata	buckbean
Nuphar polysepalum	spatter-dock
Pedicularis racemosa	sickletop lousewort
Potamogeton amplifolius	large-leaved pondweed
Potentilla palustris	purple cinquefoil
Pterospora andromedea	pinedrops
Pyrola asarifolia	pink wintergreen
Pyrola picta	white-vein wintergreen
Pyrola secunda	one-sided wintergreen
Senecio serra	tall butterweed
Spagnum argustifolium	
Spagnum mendocinum	
Spiranthes ramonzoffiana	hooded ladies-tresses
Tiarella trifoliata	foamflower
Viola orbiculata	round-leaved violet
Viola palustris	marsh violet
Xerophyllum tenax	beargrass
FERNS and FERN ALLIES	
Dryopteris filix-mas	male fern
Equisetum arvense	field horsetail
Lycopodium annotinum	stiff clubmoss

Table 2. Vascular plants identified on or around Mary's Frog Pond, Montana.

twice at a depth of 120 cm and again at 60 cm depth. Arceuthobium (mistletoe) is present with some regularity throughout the pollen core. There are various species of Arceuthobium which are parasitic on Pinus, Abies, Pseudotsuga menziesii, Larix, Thuja or Picea (Hitchcock and Cronquist, 1981). No distinction of Arceuthobium beyond genus can be made with accuracy.

Algae

The acid resistant algae are represented by five species of Pediastrum, Botryococcus, Scenedesmus and Spirogyra. The five Pediastrum species occur sporadically throughout the pollen core with the most consistent being Pediastrum boryanum. Pediastrum generally live on the bottoms of quiet pools and lakes (Bold *et al.*, 1987). Botryococcus show at least five distinctive peaks in the relative frequency diagram. These occur at 5 cm, 40-50 cm, 100 cm, 120 cm and 190 cm depth. The greatest increase is at 190 cm (following the fall of Mazama ash) where 2585 individual Botryococcus were counted. The increases at 100 cm and 120 cm (21% and 33%, respectively) occur directly after a dramatic increase in charcoal frequency. The Scenedesmus is quite abundant throughout much of the core with an average of 10% and a high of 30% at 145 cm depth. Scenedesmus are considered ubiquitous, occurring abundantly in many freshwater habitats (Bold *et al.*, 1987). Spirogyra is not as well represented with a trace noted at 175 cm depth and not again until 30 cm depth and continuing through the top of the core.

Pollen /Charcoal Accumulation Rates

The pollen accumulation at the bottom of the core begins at almost 10 x 10^3 grains $cm^{-2}\,yr^{-1}$, but quickly falls to around 6.5 x 10^3 grains $cm^{-2}\,yr^{-1}$ at 185 cm depth. Between 6000 yr B. P. and 2000 yr B. P. the pollen accumulation

rate displays relatively large and regular fluctuations. These vary between 9.9 x 10^3 grains cm^{-2} yr^{-1} at 90 cm depth, to 3.7 x 10^3 grains cm^{-2} y r^{-1} at 120 cm depth. The greatest pollen accumulation rate occurs at 70 cm (approximately 2100 yr B.P.) with a value of 12 x 10^3 grains cm^{-2} yr^{-1}. After 2000 yr B.P., the pollen accumulation falls, finally wavering around 5.5 x 10^3 grains cm^{-2} yr^{-1} in the most recent portion of the core.

The charcoal accumulation rate fluctuates less dramatically than the pollen except in two quite noticeable places. At 125 cm depth, the accumulation makes a dramatic leap from 1 x 10^3 grains cm^{-2} yr^{-1} to 46 x 10^3 grains cm^{-2} yr^{-1}. This peak occurs at approximately 4000 yr B.P. The charcoal accumulation rate drops back to about 1.1 x 10^3 grains cm^{-2} yr^{-1} at 120 cm depth, then jumps again to 16 x 10^3 grains cm^{-2} yr^{-1} at a depth of 105 cm (around 3300 yr B.P.). From 0 cm to 60 cm (approximately the last 2000 yr B.P.), the charcoal accumulation rate averages around 2.1 x 10^3 grains cm^{-2} yr^{-1}.

Ratios

Ratios of charcoal to total terrestrial pollen further exemplifies the tremendous amount of charcoal deposited in the sediments at the two localities described above. ' At 125 cm depth the ratio of charcoal to terrestrial pollen shifts from 0.2 to 6.7 (a larger value indicating greater charcoal to pollen). Another jump occurs at 105 cm with an increase of charcoal to terrestrial pollen increases from 0.3 to 2.7. The ratio of charcoal to terrestrial pollen throughout the remainder of the sediment core averages 0.25. The ratio at the top of the core is 0.5.

The ratio of nonarboreal pollen (NAP) to arboreal pollen (AP) illustrates the dominance of Pinus throughout much of the core. The AP

pollen dominates the NAP consistently through the pollen record except for the period directly following the fall of Mazama ash. Here the ratio reflects the dominance of NAP at a ratio of 0.8. After this initial dominance of NAP, the AP consistently exceeds the overall pollen record at Mary's Frog Pond by factors ranging from 0.05 to 0.4 (Figure 7).

Pollen Zones

Four pollen zones were delineated from the core for ease in the discussion and interpretation of the pollen assemblage (for a discussion on how zones were determined see Methods). The zones represent "a body of sediment distinguished from adjacent sediment bodies by differences in kind and amount of its contained fossil pollen grains and spores, which were derived from plants existing at the time of deposition of the sediment" (Birks and Gordon, 1985). Zone I is from 190 cm to 188 cm corresponding to about 6800 yr B.P. to 6500 yr B.P. Zone II ranges from 188 cm to 108 cm, a span dating from 6500 yr B.P. to 3500 yr B.P. The third zone covers approximately 1500 years (3500 yr B.P. to 2000 yr B.P.) extending from 108 cm to 63 cm. Zone IV is the most recent zone ranging from 2000 yr B.P. to the present (63 cm to 0 cm).

DISCUSSION

Mary's Frog Pond was cored with the expectation that it would provide a continuous record of the origins and progressive pathways of the past 6800 years which have resulted in the present-day plant community. Pollen is well preserved in the sediments facilitating the identification and successive collection of the pollen assemblage. Charcoal fragments are present and quantified for fire history interpretations. An accompanying chronology was generated from in situ macrofossils for radiocarbon dates. Thus, with good

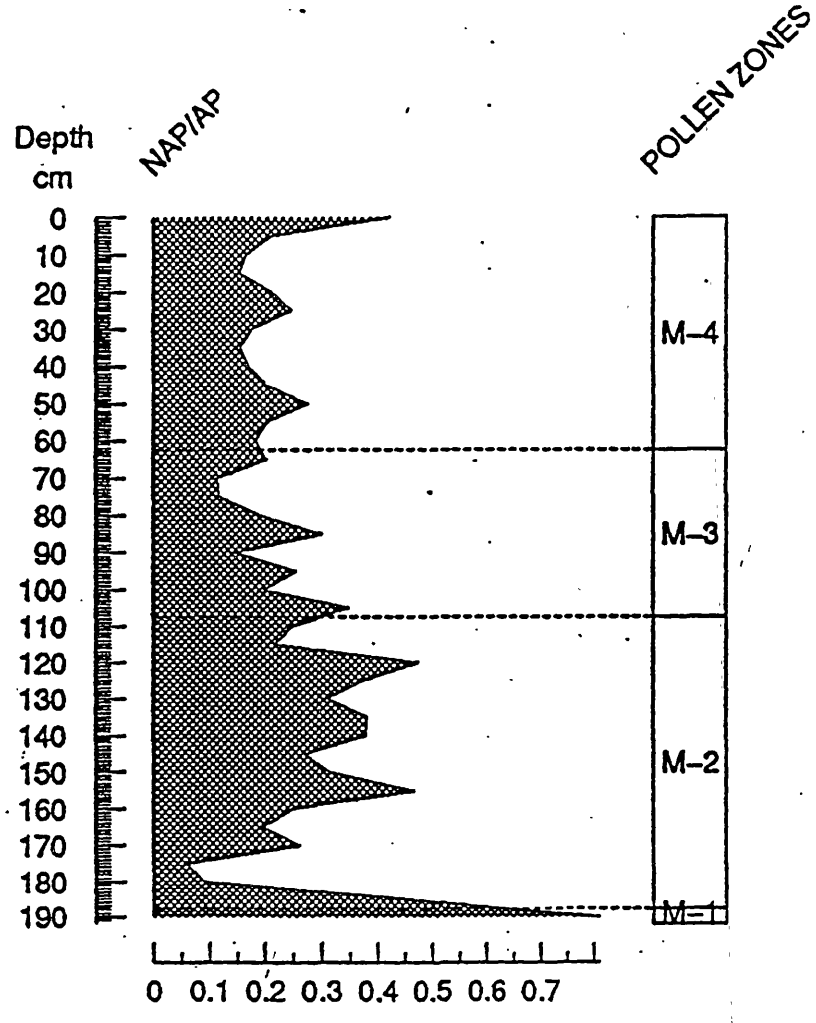

Figure 7. Ratio of NonArboreal Pollen (NAP) to Arboreal Pollen (AP).

pollen and charcoal preservation, and an adjoining time frame, the following interpretation of the core is presented.

Vegetation and Climate

Post Mazama: 6800-6200 yr B.P. *(Zone I)*

The most outstanding feature of this zone is the dominance of NAP over AP (a ratio of 0.8). This it the only place in the pollen record where NAP over shadows the AP. This results from the simultaneous abundance of Alnus, Artemisia, cheno-ams, Gramineae, and Spirea following the fall of Mazama ash . Also noteworthy is an abundance of Juniperus and Salix, plus aquatic related species including Cyperaceae, Nuphar, Botryoccus and Pterdium. A similar increase in shrubs and forbs is observed at Sheep Mountain Bog. In particular, an abundance of Physocarpus is apparent just above Mazama ash (Mehringer, 1985).

It is tempting to relate this particular species composition to the influence of Mazama ash, however, other studies suggest that ashfalls have little effect on regional vegetation. At Lost Trail Pass Bog, Mehringer, Arno and Petersen (1977), found no indication of vegetation or pollen production being influence by the ashfall. Since no samples were analyzed directly below Mazama ash at Mary's Frog Pond, the impact of Mazama ash on the surrounding vegetation remains a mystery.

Botryoccus deserves special mention since it accounts for 82% of all the pollen and microfossils in the sample directly above Mazama ash. At Lost Trail Pass, Botryoccus and Pediastrum were used to deduce the season of Mazama ashfall (Mehringer, Blinman and Petersen, 1977). Samples below and above Mazama ash contained 4300 to 6000 of these algae per squared centimeter per year. However, samples taken of Mazama ash contained only

358 Botryoccus and Pediastrum specimens. Mehringer, Blinman and Petersen (1977), conclude that during the nearly three years of ashfall from Mazama had a profound effect on the productivity of Lost Trail Pass Bog. However, the effects were short term and may have even increased vigor and pollen production. The superabundance of Botryoccus at Mary's Frog Pond would substantiate the short term effects of Mazama ash.

Pseudotsuga/Larix: 6200-3500 yr B.P. *(Zone II)*

This zone corresponds with the geological time period termed the middle Holocene. During this period, "without exception", the paleoecological record has shown an apparent warming throughout the interior Pacific Northwest and northern Great Basin (Mehringer, 1985). A ternary diagram of the pollen from three conifers, Picea, Abies and Pseudotsuga/Larix is presented (Figure 8). These three species were chosen because they are the best indicators of climate and/or site conditions of the dominate life forms present in the pollen record. The diagram unmistakably illustrates the dominance of Pseudotsuga/Larix over the other two genera during this time. The dominance of Pseudotsuga/Larix over Picea and Abies suggests a time of higher temperatures and perhaps less effective moisture.

This same phenomenon occurred at Lost Trail Pass Bog with an increase in Pseudotsuga/Larix pollen and diploxylon pines (probably lodgepole pine) replacing haploxylon pines (possibly the more cold tolerant whitebark pine) (Mehringer, Arno and Petersen, 1977). The prevalence of Pseudotsuga/Larix is further illustrated in the relative percentage diagram of these three conifers (Figure 9).

A general overview of the percentage pollen diagram in Zone II indicates a fairly consist variety of taxa present. Six taxa occur only in Zone II:

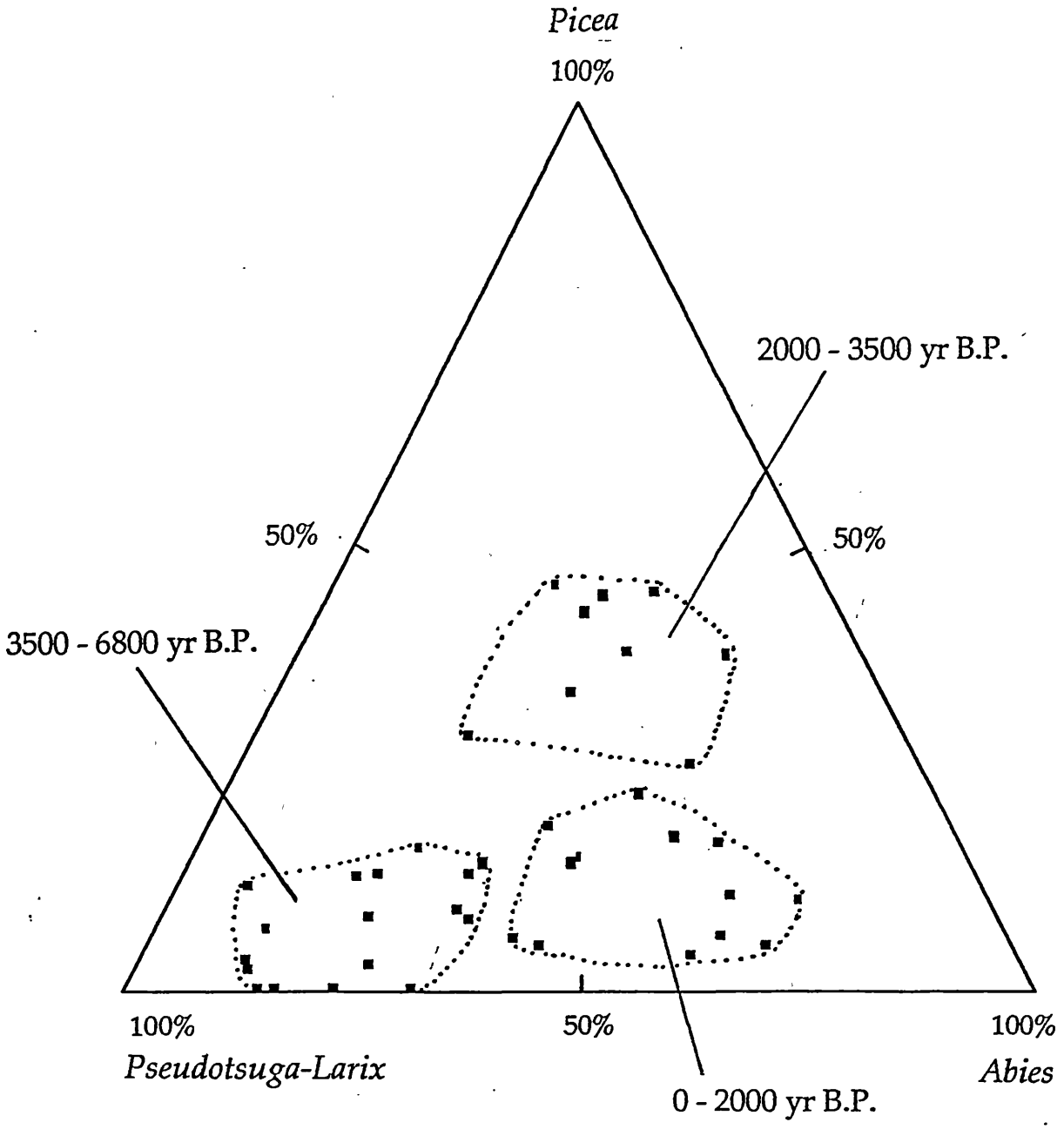

Figure 8. Ternary plot of Picea, Abies and Pseudotsuga-Larix pollen for the past 6800 years from Mary's Frog Pond, Montana. Dots represents the relative abundance of all three taxa at each of the 39 samples. Samples that fall within each particular time period are circled. This illustrates how the composition of these conifer taxa have shifted through time.

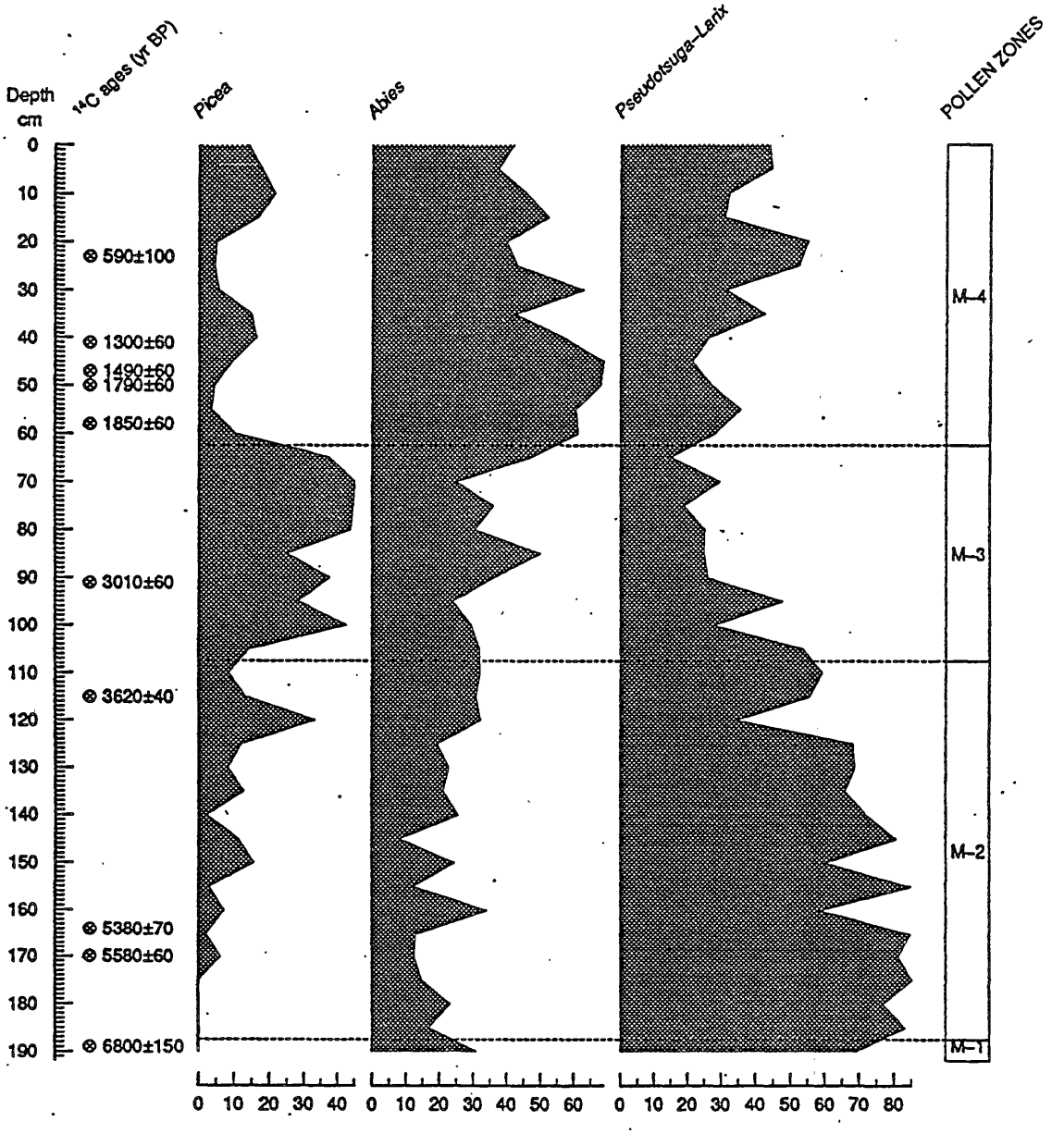

Figure 9. Relative percentage diagram of Picea, Abies and Pseudotsuga-Larix. (%Picea + %Abies + %Pseudotsuga-Larix = 100%)

Caryophylaceae, Berberis, Ribes, Liliaceae, Typha latifolia and Drosera. Although not found in great quantities, the pollen from Ambrosia-type, other Compositae, Ceanothus, Spirea, Cruciferae, Umbelliferae and Prunus-type occur consistently in this zone. This may all indicate a relative diverse plant community during this time period.

Mixed Species: 3500-2000 yr B.P. *(Zone III)*

The ternary diagram of Pseudotsuga-Larix, Picea and Abies for this time period shows a shift in the dominate plant community to a more mixed species composition (Figure 8). There appears to be about the same general relative abundance of these three conifers. This might indicate a climatic change towards cooler temperatures and more effective moisture relative to Zone II. A ratio of Picea and Abies (indicators of cooler temperatures and more effective moisture) to Pseudotsuga-Larix (warmer, drier conditions) shows the greatest ratio values to be in Zone III (Figure 10). Whereas ratios of Picea and Abies to Pseudotsuga-Larix range from 0.17 to 1.9 in Zone II (suggesting the dominance of Pseudotsuga-Larix), ratios in Zone III range from 0.9, to a high of 5.7 (indicating the dominance of Picea and Abies).

This apparent shift towards cooler and moister conditions was also reported at both Smeads Bench Bog and Lost Trail Pass Bog. At Smeads Bench Bog, this period corresponds with a closed canopy forest interpreted to be an Abies grandis habitat type (Chatters and Leavell, 1994). This habitat type indicates a moist site which may correspond with frost pockets (Pfister *et al.*, 1977). At Lost Trail Pass Bog, the Pseudotsuga has greatly declined by 4000 yr B.P. and there is a marked increase in diploxylon pine and haploxylon pine (presumably whitebark pine). Mehringer, Arno and Petersen (1977), interpret this as a climatic shift indicative of more effective moisture availability.

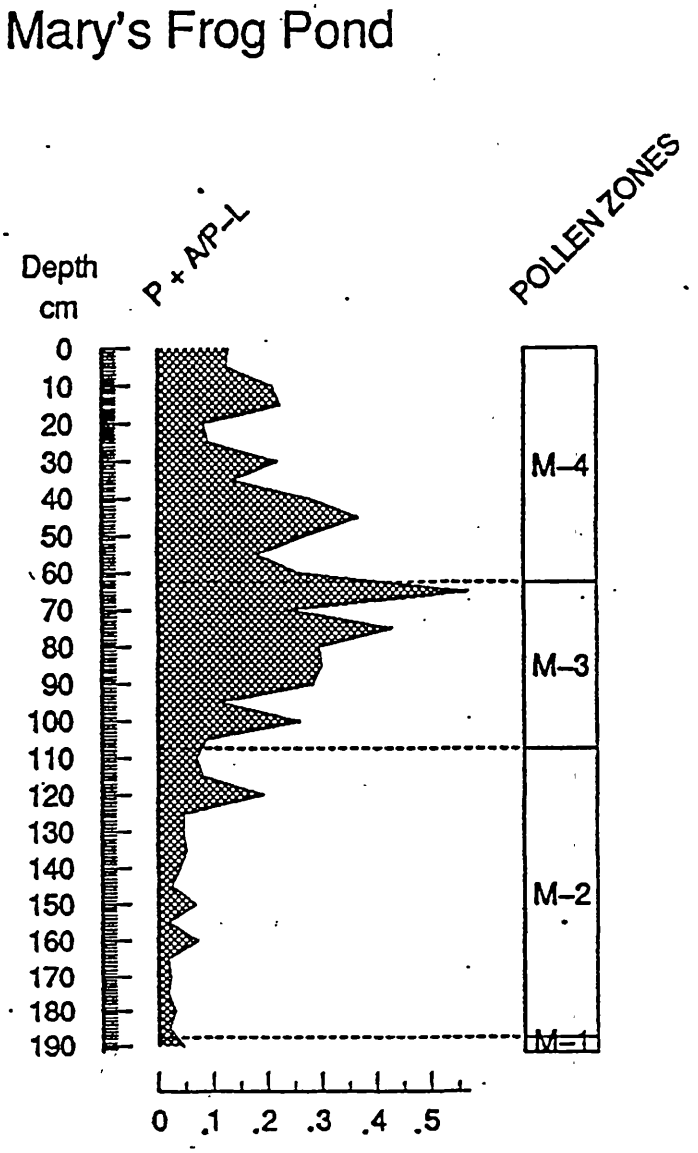

Figure 10. Ratio of Picea and Abies pollen (indicators of cooler temperatures and more effective moisture) to Pseudotsuga/Larix pollen (indicator of warmer, drier conditions). P + A = sum of Picea and Abies; P - L = Pseudotsuga/Larix.

The number of different species remains relatively high as in Zone II with the addition of Quecus, Primulaceae, Menyanthes and Scheuchzeria. This zone also contains the widest variety of spores.

Present-day: 2000 yr B.P.-Present *(Zone IV)*

Zone IV represents the most recent time period and seems to correlate with the plant community present at Mary's Frog Pond today. The ternary diagram reveals another shift of the conifer composition towards a preponderance of Abies and Pseudotsuga/Larix (Figure 8). The relative frequency diagram of these three conifers clearly shows the decline of Picea, the dominance of Abies and co-dominance of Pseudotsuga/Larix (Figure 9). Presently, Mary's Frog Pond is in an Abies lasiocarpa habitat type mixed with Larix occidentalis.

Tsuga heterophylla appears in the pollen record for the first time in this zone. This corresponds with results at Big Meadow in northwestern Washington (Mack *et al.*, 1978b), Hager Pond in northern Idaho (Mack *et al.*, 1978a; Mehringer, personal communication) and Smeads Bench Bog in northwestern Montana (Chatters and Leavell, 1994) where Tsuga heterophylla did not appear until after 2000 yr B.P.

Pines

Pinus dominates the entire pollen record comprising as much as 80% of the terrestrial pollen counted. There are several incidents where the pine pollen declines noticeably and deserves some interpretation. The first local is at the bottom of the core in Zone I (discussed above) where the relative frequency of Pinus is 50%. After a steady increase, pines decline again at 155 cm depth. This corresponds with a distinct increase in the relative abundance

of Juniperus, Alnus and Artemisia so might be a result of constraint in the percentage diagram. The dip to 51% at 120 cm depth directly follows a huge accumulation of charcoal fragments observed at 125 cm depth. Presumably, the decline in Pinus is at least partially due to the preceding period of fires. The last place where the Pinus declines is at the very top of the core. This is also marked by an increase in NAP to AP (particularly Alnus) and charcoal to terrestrial pollen. This may again reflect the influence of fire on the vegetation community.

A distinction between diploxylon (i.e. lodgepole pine and ponderosa pine) and haploxylon pine (i.e. whitebark pine) was made during pollen identification whenever possible. A percentage diagram of diploxylon to haploxylon pine clearly shows the dominance of diploxylon through out the pollen sequence (Figure 6). This may be a result of processing the pollen in the laboratory (resulting in breaking or tearing of grains) or a misidentification of pollen type. However, it is preferable to conclude the dominance of diploxylon pines is a consequence of the particular elevation, climatic conditions and ecological setting of Mary's Frog Pond. An increase in haploxylon pines over diploxylon pines was used at Lost Trail Pass Bog (Mehringer, Arno and Petersen, 1977) and Sheep Mountain Bog (Mehringer, 1985) as an indication of shifting climatic conditions. At Mary's Frog Pond, an interpretation of climatic variations must be made using the other conifers present at the site.

Fire History

The examination of the charcoal to total terrestrial pollen ratio at Mary's Frog Pond highlights two dramatic periods of increased charcoal in the core with a backdrop of low to moderate charcoal abundance throughout the

remainder of the core (Figure 11). These two charcoal peaks (at 125 cm and 105 cm depth) are discussed in more detail below. The charcoal to total terrestrial ratios average around 0.35 suggesting small or medium intensity fires. This is the same scenario that occurred at Lost Trail Pass Bog where some charcoal was present in all the samples. Mehringer, Arno and Petersen, 1977, interpreted this as evidence for "frequent small or low to medium intensity fires in the Bitterroot Mountains. Catastrophic fires in the Lost Trail Pass area are apparently the exception."

The presence of moderate amounts of charcoal throughout the sediment core is substantiated by the charcoal accumulation rates per centimeter squared per year (Figure 12). Aside from the two periods of tremendous charcoal accumulation at 125 cm and 105 cm depth, the graph illustrates that charcoal influx has remained relatively constant (and low) for the past 6800 years.

Some discussion has been given to additional interpretations of fire history based on size-classes of microscopic charcoal (MacDonald *et al.*, 1991). Tolonen (1986) argued a higher proportion of large charcoal fragments indicates periods when fires burned close to the basin they are deposition in. Clark (1988) studied the transport of charcoal particles and found that fragments greater than 50 μm diameter indicate local fires. It is also thought that finer ash particles indicate a more rigorous or distant fire (Patterson *et al.*, 1987).

The charcoal fragments at Mary's Frog Pond were separated by the following size classes: 25-50μm, 50-100μm and greater than 100μm. A diagram of these three size classes based on accumulation of grains per centimeter squared per year illustrates that majority of the microscopic charcoal fragments are within the 25-50μm category (Figure 13). The

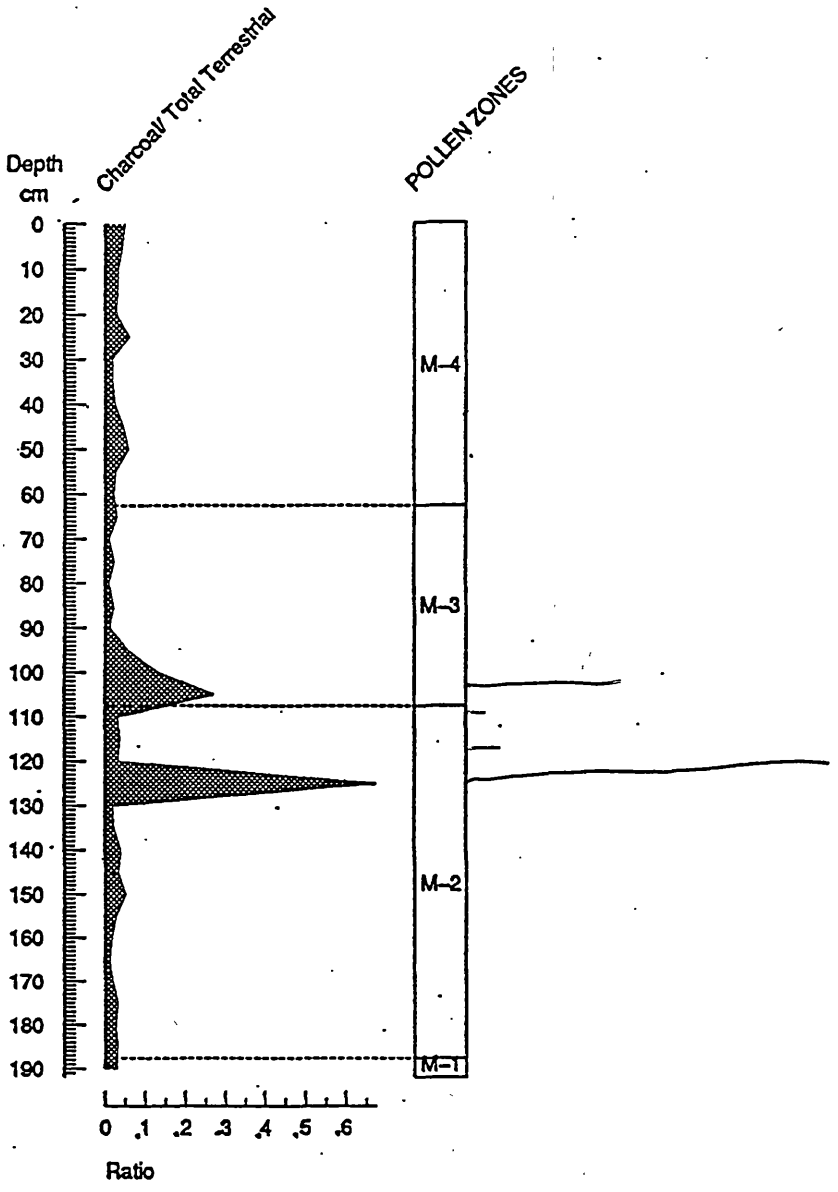

Figure 11. Ratio of total charcoal fragments to total terrestrial pollen grains.

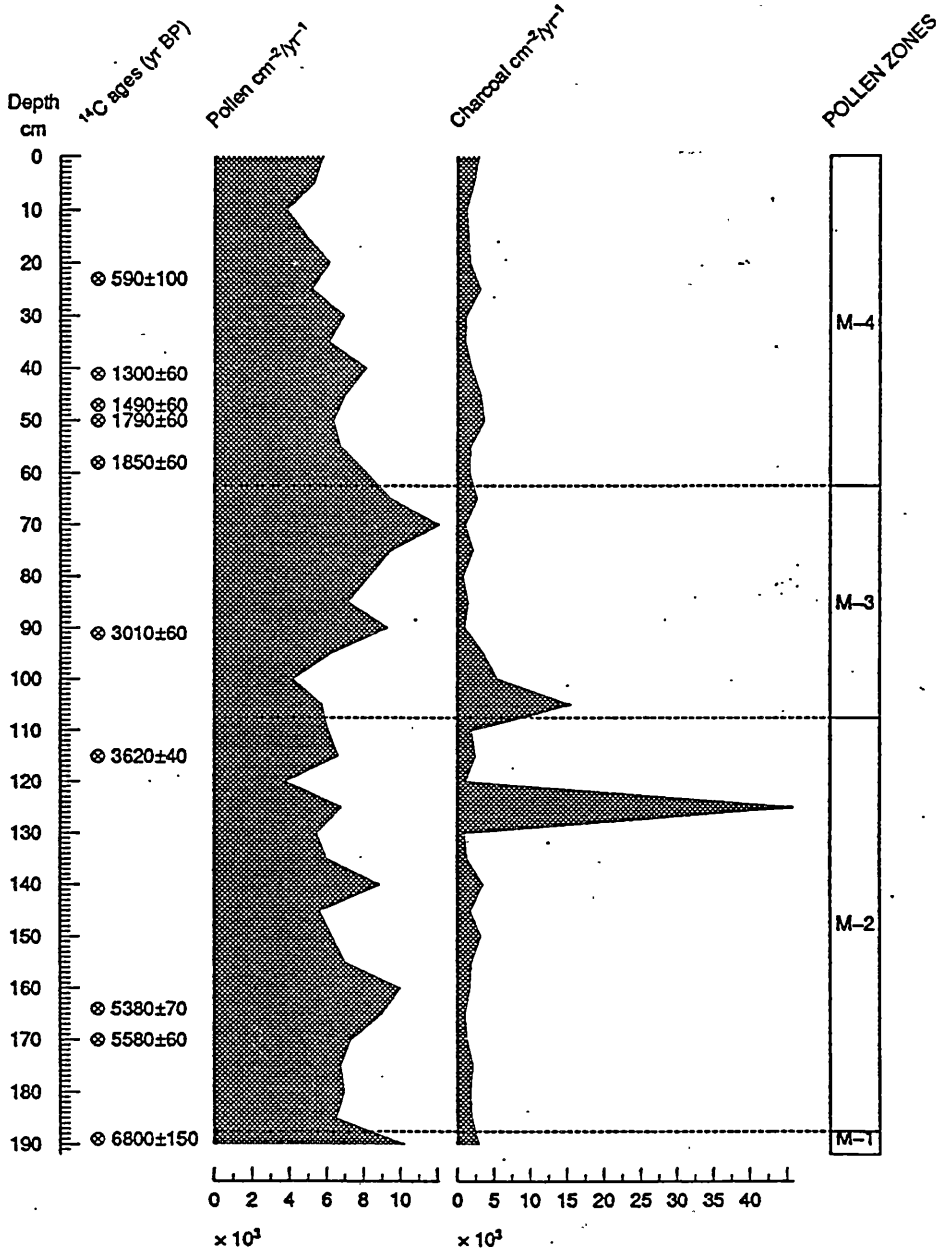

Figure 12. Pollen grains and charcoal fragments accumulation rates per cm^{-2} $year^{-1}$ at Mary's Frog Pond, Montana.

frequency of charcoal in the other two size classes are essentially identical to each other until the top 50 cm of the core where there is more of the 50-100 μm than greater than 100μm.

Three interpretations can be offered for the dominance of charcoal fragments in the smallest size. First, this could be a by-product of the laboratory processing procedure. It is conceivable that the charcoal fragments were broken down into small fragments from the amount of mixing necessary to process the samples. Second, it could be indicative of the proximity of fires to the pond. It is reasonable to conclude that smaller charcoal fragments will be transported greater distances. Lastly, the abundance of small charcoal particles might indicate constant rigorous fires. Based on other studies from this region and the pollen composition of the entire core, this last interpretation seems most unlikely. It is more reasonable to suggest that fires occurred at low intensities at frequent intervals in various locations around the region. Consequently, the charcoal influx is constant, yet never overly dramatic (except in the two periods described below).

Two Charcoal Peaks at 3300 yr B.P. and 4000 yr B.P.

Two charcoal peaks stand out above all others when looking at charcoal to total terrestrial ratios and charcoal accumulation rates per centimeter squared per year. These occur at 125 cm depth (approximately 4000 yr B.P.) and at 105 cm depth (about 3300 yr B.P.). Similar patterns occur with the ratios, accumulation rates and pollen diagram at these two places in the sediment core, however, to facilitate discussion and highlight differences, they will be discussed separately.

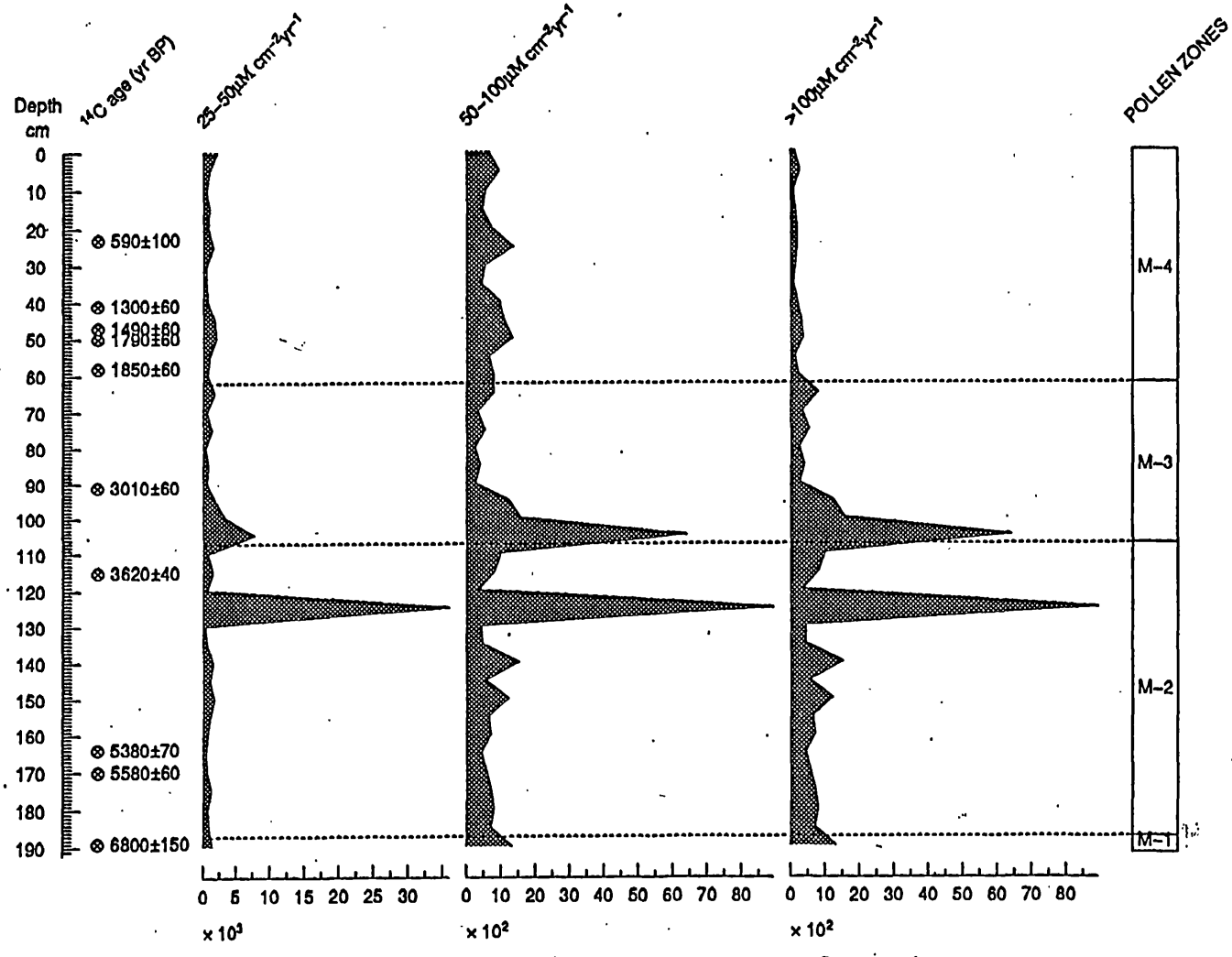

Figure 13. Charcoal accumulation rate of three size classes per cm^{-2} $year^{-1}$. (Note different scales between 25-50 μm and 50-100μm, >100μm.)

The charcoal peak at 125 cm in the biggest of the two (Figure 11). Whereas from Mazama ash up to this point the charcoal accumulation rate averages 2000 grains $cm^{-2}\,yr^{-1}$, this peak contains 45,804 grains $cm^{-2}\,yr^{-1}$; more than a twenty-two fold increase! Depending on variations in sedimentation rate, a dramatic increase in charcoal accumulation might be a by product of more years being represented in fewer centimeters (Hemphill, 1983). However, the sediment deposition rate at Mary's Frog Pond remains relatively constant throughout the core (Figure 4). Therefore, it might be interpreted that this distinct episode of tremendous charcoal accumulation does represent a period of greater fire frequency or intensity relative to all other portions of the pollen core. The ratio of charcoal to terrestrial pollen further accentuates this point where the ratio jumps from 0.19 at 130 cm depth to 6.73 at 125 cm depth.

Several other things occur in the pollen record and organic content of the sediments around the same time as this increase in charcoal. Just after this peak in charcoal, the ratio of NAP to AP pollen reaches its highest value since Mazama ash at 120 cm depth. The relative frequency of Alnus increases and Ceanothus is present in the sample at 120 cm depth (both taxa are frequently associated with fires). Additionally, the overall accumulation of pollen grains $cm^{-2}\,yr^{-1}$ declines from 6808 grains $cm^{-2}\,yr^{-1}$ before the charcoal influx, to 3748 grains $cm^{-2}\,yr^{-1}$ afterwards (Figure 12). Lastly, at 125 cm depth, the percent of organic carbon in the sediments dips from 31.9% to an all time low of 19.5% (Figure 5).

The aquatics appear to be effected by the charcoal influx as evidenced by the distinct absence of Nuphar pollen at this point and the significant peak in Botryoccus. This increase in the Botryoccus is interesting for it might parallel the findings of an experiment conducted at Hubbard Brook, New Hampshire.

All the vegetation in a small forested watershed was cut down and all the regrowth the next spring was eliminated. Due to the removal of forest canopy cover, the light and water temperatures increased. As a result, the nitrate levels skyrocketed which led to a prolific growth of algae (Bormann and Likens, 1979). Could the increase in algae at Mary's Frog Pond be due to the reduction in forest canopy surrounding the pond because of catastrophic fires?

Many of these same patterns were observed in the charcoal peak at 105 cm depth, but to a lesser degree. Charcoal grains per centimeter squared per year in this sample was 15,516 (about an eight fold increase from the sample just below at 110 cm depth). The charcoal to terrestrial pollen ratio jumps from 0.317 to 2.698. The pollen accumulation rate responds to the increased charcoal as evidenced by a decrease from approximately 6000 grains $cm^{-2}\,yr^{-1}$ before the peak to around 4000 grains $cm^{-2}\,yr^{-1}$ afterwards. The Alnus and algae increase in relative frequency and Ceanothus is present in the sample. Once again, the percent organic content dips from 45.3% before the charcoal peak to 19.8% when the charcoal influx occurs.

In order to place these charcoal peaks in time, it is interesting to note that the biggest one occurs in Zone II just before the transition between Zone II and Zone III. This is when it is inferred that the conifer composition changes from a Pinus and Pseudotsuga/Larix forest to Pinus with a more even mixture of Pseudotsuga/Larix, Abies and Picea. The change in forest types has been interpreted as a potential change in climatic conditions from warmer, less effective moisture to cool, moister condition. The second charcoal peak in Zone III is also near the transition between zones.

SUMMARY AND CONCLUSIONS

This study was initiated to elucidate the past vegetation communities and fire history of the area surrounding Mary's Frog Pond in the Bitterroot Mountains, Montana. A glimpse of how the plant assemblages have shifted through time can contribute to some general interpretations of the ecological conditions that may have been present at a particular time in the past. The microscopic charcoal provides one method for looking at disturbance and what impact it may or may not have had on the surrounding vegetation. A summary of the pollen and charcoal analysis at Mary's Frog Pond follows.

1. The plant composition initially following Mazama ash is unique from all other portions of the core due to the dominance of NAP to AP. This phenomena also occurs as Sheep Mountain Bog.
2. Since Pinus dominates all other conifers at Mary's Frog Pond, the composition in relative frequency of Picea, Abies and Pseudotsuga-Larix was used to illustrate shifts in plant assemblages. Based on these three taxa, three distinct periods are evident after the initial rise in NAP up to the present. A general interpretation of moisture and temperature was extrapolated from these results.
3. From 6200-3500 yr B.P., the Pseudotsuga-Larix pollen dominates over Picea and Abies. This suggests an apparent warming that has been observed at numerous other sites in the interior Pacific Northwest.
4. A shift towards cooler temperatures and more effective moisture was suggested between 3500-2000 yr B.P. by the same general abundance of all three taxa. This climatic trend was observed at Smeads Bench Bog in the Cabinet Mountains and Lost Trail Pass Bog in the Bitterroot Mountains.

5. By 2000 yr B.P. the forest communities seems to resemble the habitat presently surrounding Mary's Frog Pond. Abies and Pseudotsuga-Larix tend to dominate over the Picea.

6. Aside from two exceptions, the overall fire history based, on microscopic charcoal fragments, seems to suggest frequent, low to medium intensity burns throughout the 6800 years examined. Two peaks in charcoal fragments were observed between 3300 yr B.P. and 4000 yr B.P. These have been interpreted as periods of increased fire activity based on microscopic charcoal, pollen accumulation, vegetation composition and organic content of the sediments.

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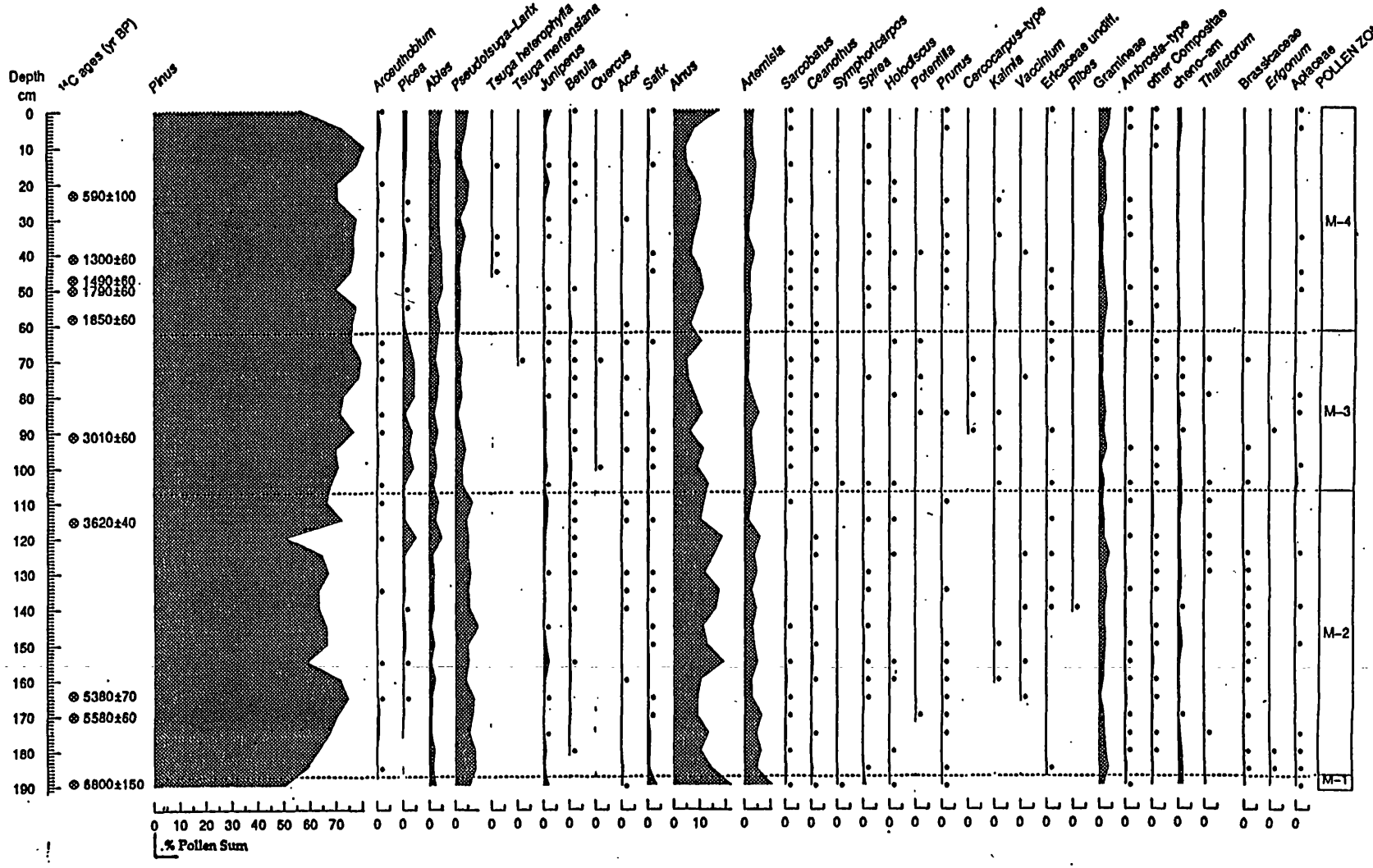
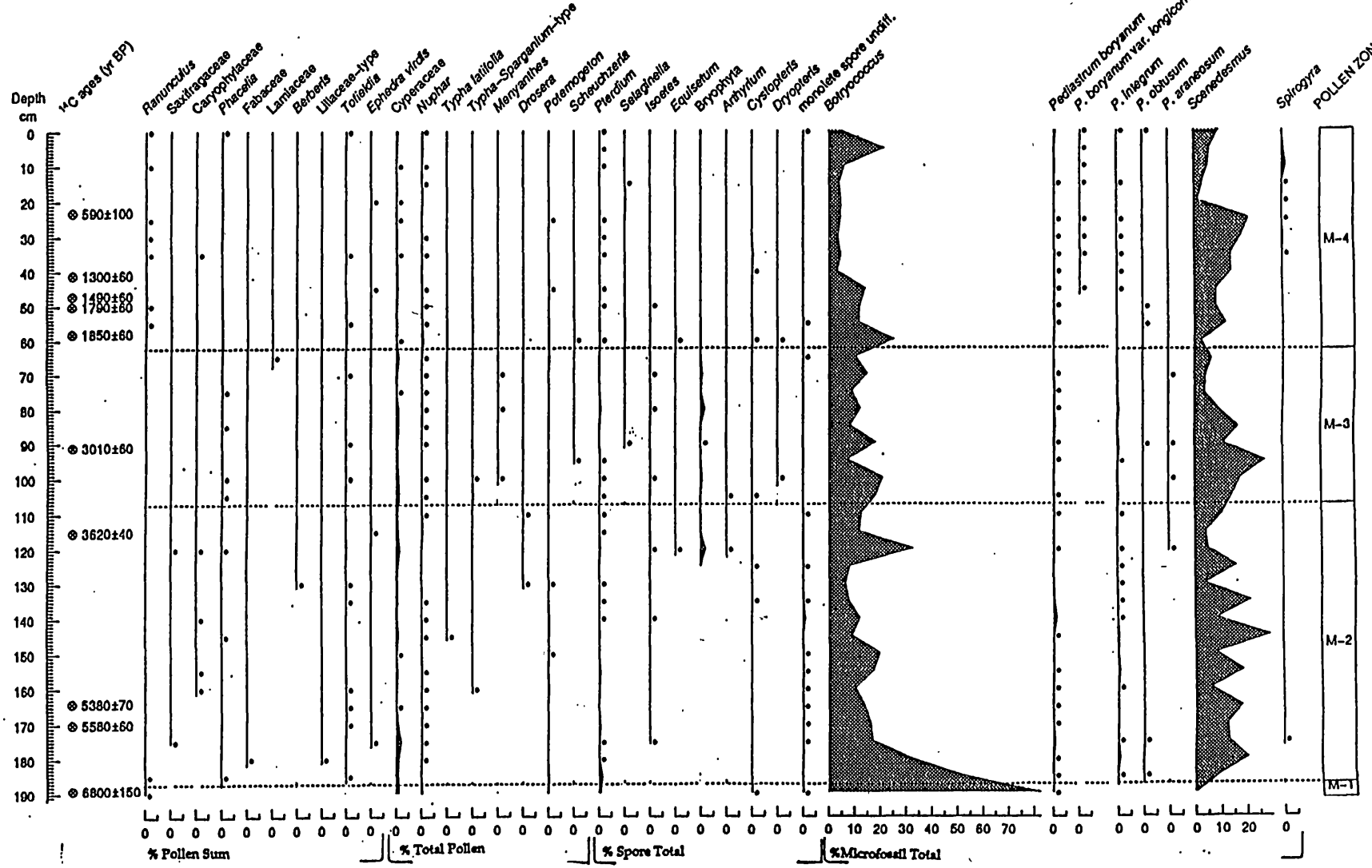
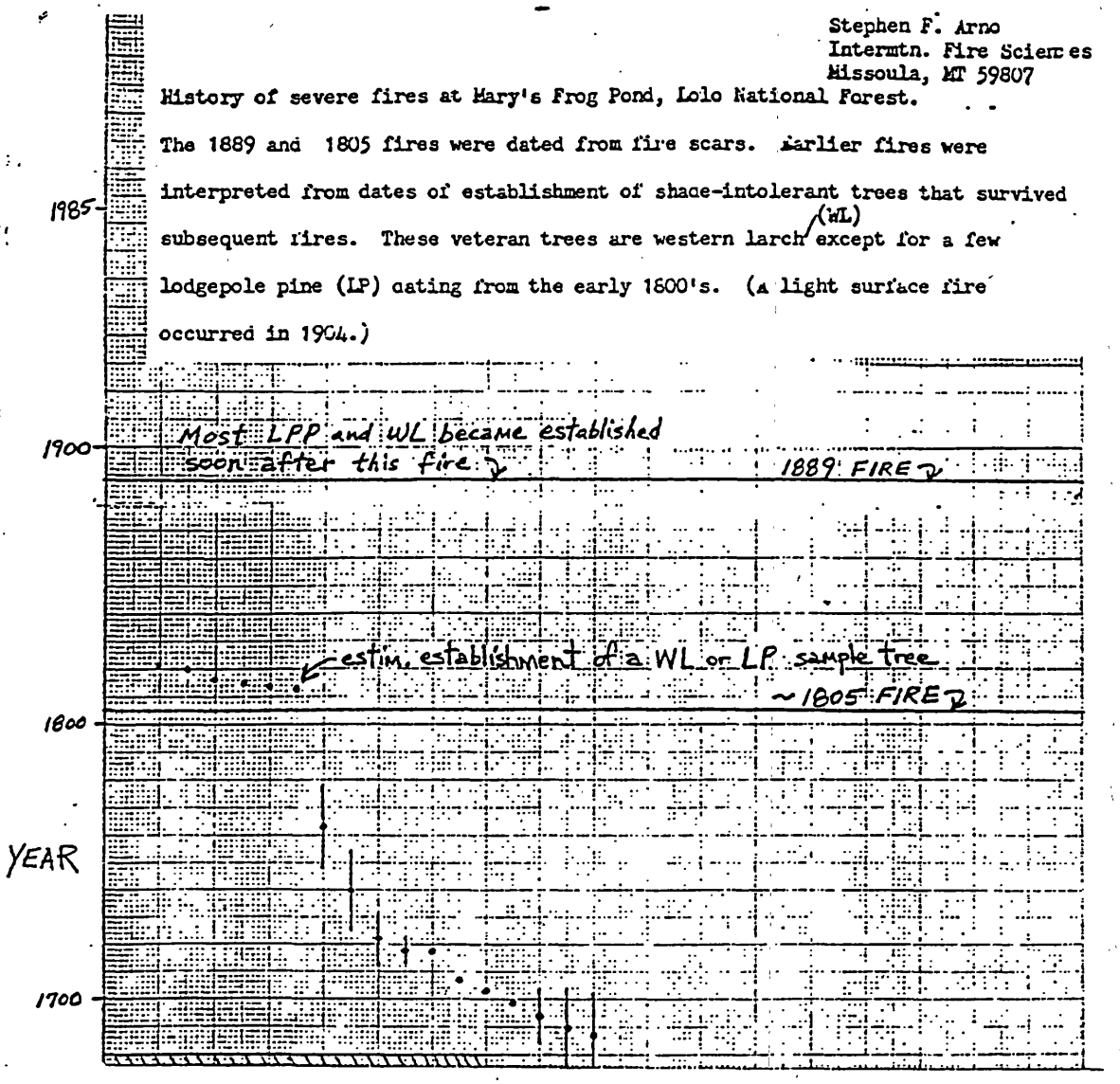

Depth cm
14C ages (yr BP)
Pinus
Arceuthobium
Picea
Abies
Pseudotsuga–Larix
Tsuga heterophylla
Tsuga mertensiana
Juniperus
Betula
Quercus
Acer
Salix
Alnus
Artemisia
Sarcobatus
Ceanothus
Symphoricarpos
Spirea
Holodiscus
Potentilla
Prunus
Cercocarpus–type
Kalmia
Vaccinium
Ericaceae undiff.
Ribes
Gramineae
Ambrosia–type
other Compositae
chenо–am
Thalictrum
Brassicaceae
Eriogonum
Apiaceae
POLLEN ZONES
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
590±100
1300±60
1490±60
1790±60
1850±60
3010±60
3620±40
5380±70
5580±60
6800±150
M–4
M–3
M–2
M–1
0 10 20 30 40 50 60 70
0 0 0 0 0 0 0 0 0 0 0 0 0 10
0 0 0 0 0 0 0 0 0 0 0 0 0


Depth cm
14C ages (yr BP)
Ranunculus
Saxifragaceae
Caryophyllaceae
Phacelia
Fabaceae
Lamiaceae
Berberis
Liliaceae-type
Tofieldia
Ephedra viridis
Cyperaceae
Nuphar
Typha latifolia
Typha-Sparganium-type
Menyanthes
Drosera
Potamogeton
Scheuchzeria
Pteridium
Selaginella
Isoetes
Equisetum
Bryophyta
Anthyrium
Cystopteris
Dryopteris
monolete spore undiff.
Botryococcus
Pediastrum boryanum
P. boryanum var. longicorne
P. integrum
P. obtusum
P. araneosum
Scenedesmus
Spirogyra
POLLEN ZONES
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
590±100
1300±60
1480±60
1790±60
1850±60
3010±60
3620±40
5380±70
5580±60
6800±150
M-4
M-3
M-2
M-1
0 0 0


Stephen F. Arno
Intermtn. Fire Sciences
Missoula, MT 59807
History of severe fires at Mary's Frog Pond, Lolo National Forest.
The 1889 and 1805 fires were dated from fire scars. Earlier fires were interpreted from dates of establishment of shade-intolerant trees that survived subsequent fires. These veteran trees are western larch (WL) except for a few lodgepole pine (LP) dating from the early 1600's. (a light surface fire occurred in 1904.)
1985
1900
1800
1700
YEAR
Most LPP and WL became established soon after this fire
1889 FIRE
estim. establishment of a WL or LP sample tree
~1805 FIRE

APPENDIX B: Fire history at Mary's Frog Pond for the past 300 years.